Investigation of Testing Methods to Determine Long-Term Durability of Wisconsin Aggregates

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FINAL REPORT

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16. Abstract

Approximately 10 to 11 million tons of aggregates are utilized in transportation infrastructure projects in Wisconsin annually. The quality of aggregates has a tremendous influence on the performance and durability of roadways and bridges. In this Phase II research study, detailed statistical analyses were performed on over 1,000 sets of historical aggregate test results and the experimental results from the Phase I study. Test results from other states were analyzed as well. Aggregate tests were performed on 12 known marginal or poor Wisconsin aggregates to specifically address test performance of such aggregates. Selected aggregates were scanned using X-ray computed tomography to assess the effects of freeze-thaw and sodium sulfate exposure on the internal void system. The results of multi-parameter logistic regression analyses show that the pass/fail outcomes of the Micro-Deval test can be predicted when LA abrasion, absorption, and sodium sulfate soundness test results are known. The unconfined freeze-thaw test outcomes cannot be predicted from results of other tests (not correlated). Therefore, the unconfined freeze-thaw test should be part of any test protocol as it measures an aggregate characteristic that cannot be obtained from other tests. The percentiles associated with any proposed acceptance threshold limits for various aggregate tests should be determined using the statistical data provided.

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EXECUTIVE SUMMARY

Approximately 10 to 11 million tons of aggregates are used in transportation infrastructure projects in Wisconsin annually; therefore, the quality of aggregates has a tremendous influence on the performance and durability of roadways and bridges. In this Phase II research study, detailed statistical analyses were performed on over 1,000 sets of historical aggregate test results and the experimental results from the Phase I study performed in 2005, and test results from other states were analyzed. Aggregate tests were performed on twelve known marginal or poor Wisconsin aggregates to specifically address test performance of such aggregates.

The results of logistic multi-parameter regression analyses show that the pass/fail outcomes of the Micro-Deval test can be predicted when Los Angles (LA) abrasion, absorption, and sodium sulfate soundness test results are known. Two 3-parameter equations and one 4-parameter equation are proposed for predicting the outcomes of the Micro-Deval test for each threshold loss limit. These equations could correctly predict all (100%) of the Micro-Deval outcomes in the 69 sets of tests performed under the Phase I study (using 18% loss limit).

The unconfined freeze/thaw test outcomes cannot be predicted from results of other tests (not correlated). Although designed to be a rapid substitute for the freeze/thaw test, the sodium sulfate soundness test is not correlated with the unconfined freeze/thaw results. The unconfined freeze/thaw test should be part of any test protocol, because it measures an aggregate characteristic that cannot be obtained from other tests.

The research team recommends that the threshold limits placed on various test outcomes consider the statistical distribution of various test results for Wisconsin aggregates. A threshold based on percentile level could preclude specification of threshold levels that would be unrealistically high. For example, the recommended LA abrasion test limit of 50% in the Phase I study corresponds with the 99.6 percentile of all LA abrasion test results in the Wisconsin database. Such a high loss limit means that only 0.4% of all aggregate sources in Wisconsin would not pass the 50% loss limit. This report provides percentile levels for all the tests within the Wisconsin database, which can be used to assess the relative impact of various threshold limits.

Twelve aggregate samples were provided to the research team by the Wisconsin Department of Transportation (WisDOT). These aggregate sources were considered to be of marginal or poor quality by WisDOT. These aggregates were selected because acceptable or good-quality aggregates were well represented in the tests performed under Phase I study. All coarse aggregate samples were subjected to LA abrasion, absorption, specific gravity, sodium sulfate soundness, unconfined freeze/thaw, and Micro-Deval tests.

The predicted pass/fail Micro-Deval outcomes (at 18% threshold level) were correct for eleven out of the twelve aggregate samples tested in Phase II, in addition to the 69 out of the 69 samples tests performed in the Phase I study. The lone sample in which the predicted and actual Micro-Deval outcomes were different was from a complex geologic formation described by WisDOT as “felsic meta-volcanic quartz-sericite schist and quatzofeldspathic gneiss.” For this sample, the measured unconfined freeze/thaw losses were high (11.9% loss or 89 percentile level). Therefore, we recommend including the unconfined freeze/thaw test in any test protocol, and performing the Micro-Deval test for aggregates with the unconfined freeze/thaw loss of more than 6% (75 percentile).

Although not included in the original project scope, the research team performed high-resolution X-ray computed tomography (CT) scans on six aggregate sources that were subjected to freeze/thaw testing and sodium sulfate soundness testing. The scans were conducted at the Argonne National Laboratory's Advanced Photon Source (APS) facility near Chicago, Illinois. The virgin aggregates were also scanned. High-resolution and three-dimensional images of the inside of these aggregates were obtained. Specialized software was used to analyze data, including void spaces. Porosity analysis of the investigated aggregates demonstrated that freeze/thaw and soundness tests significantly increased the connected pore space and induced cracks in the solid material. Analysis also demonstrated there is no trend or correlation between the increase in pore space resulting from freeze/thaw and that induced by sodium sulfate soundness test. The results of the CT investigation are also included in this report (Chapter 5).

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CHAPTER 1

INTRODUCTION

1.1 Background and Problem Statement

Aggregates constitute a substantial portion, in cost and volume, of roadway and bridge construction in the State of Wisconsin and elsewhere. Approximately 10 to 11 million tons of aggregates are used in transportation infrastructure projects in Wisconsin annually. Aggregates are significant components of roadway base courses, asphalt concrete pavements, Portland cement concrete pavements, and bridge/culvert structures; therefore, the quality of aggregates has a tremendous influence on the performance and durability of roadways and bridges. Aggregates have a wide range of applications in highway construction, including unbound base course layers, asphaltic concrete, and Portland cement concrete. Depending on the type of application and exposure conditions, the aggregate properties required for effective performance may change.

As sources of quality aggregates dwindle and new recycled/reclaimed aggregates are introduced, it is important that the quality of aggregates used in construction be assessed and controlled through appropriate testing. There are a number of aggregate tests that have been performed routinely on all aggregate sources in Wisconsin for decades, the results for which are kept in a database by the Wisconsin Department of Transportation (WisDOT). This database (containing 2,052 sets of tests) was made available for analysis in this study. This database is an extremely important resource that could allow statistically meaningful analyses of the results.

In the Phase I component of this study performed in 2005, Weyers et al.[1] reported the test results for 69 Wisconsin aggregate sources. These tests included standard tests that WisDOT routinely performs, as well as newer tests. The tests routinely performed by WisDOT include specific gravity (ASTM C127), absorption (ASTM C128), soundness using sodium sulfate (ASTM C88), lightweight pieces in aggregates (ASTM C123), unconfined freeze/thaw test (AASHTO T103), and the Los Angeles (LA) abrasion and impact test (ASTM C131). Weyers et al.[1] performed a number of other tests such as the Micro-Deval test (AASHTO TP 58), Aggregate Crushing value (British Standards 812-110), and freeze/thaw testing of concrete (ASTM C666).

Weyers et al. recommended a number of test protocols to be used for qualification of Wisconsin aggregates. The three test protocols were directed at applications involving unbound aggregates, Portland cement concrete aggregates, and bituminous aggregates. They proposed the vacuum absorption test (modified from the standard absorption test), the Micro-Deval test, the LA abrasion and impact test, the freeze/thaw in concrete test, and the lightweight pieces in aggregates test. The Micro-Deval test was included in all test protocols.

The Phase I research team briefly discussed the available database of Wisconsin test results and performed limited histogram analyses on them. This database includes over 2,000 sets of test results from various pit and quarry aggregate sources in Wisconsin; however, detailed analyses of database records were not performed in the Phase I study. This important data source could be used to statistically evaluate the various test results and to ascertain whether existing test methods could, either individually or in combination, be statistically equivalent to any of the existing or new tests such as the Micro-Deval test.

Many of the newer tests proposed in Phase I have uncertain “acceptance” levels. The acceptance (threshold) level (limit) is used to distinguish the “good” or “passed” tests from the “poor” or “failed” aggregates. For example, there is no universal agreement in the research community about the appropriate threshold limit for the Micro-Deval test. This uncertainty could be entered into the statistical evaluation processes.

The database records and results of the Phase I test program could potentially be used to perform multivariate regression analyses among different test results. This Phase II study addresses this issue in detail. The Phase I study included one-on-one (y versus x) linear regression analyses done on individual test results; however, such analyses would not reveal if a combination of two or more tests (e.g., LA abrasion and absorption tests) could yield the same good/poor (pass/fail) outcome as the recommended Micro-Deval tests, if a particular set of acceptance limits are used.

There is general consensus that the freeze/thaw damage to unbound aggregates would be different from freeze/thaw damage in concrete. Weyers et al.[(1)] point out the differences between the two tests. The unconfined aggregate will sustain damage as a result of its expansion due to freezing; however, the freeze/thaw damage in concrete results in part from the restraint of aggregate expansion by the paste. The relative stiffness of the aggregate and the paste is expected to influence the degree of stress generated. Therefore, while the unconfined freeze/thaw tests (AASHTO T103) is not expected to correlate well with the freeze/thaw test in concrete (ASTM C666), it is conceivable that a combination of the AASHTO T103 test and another test (which may directly or indirectly assess aggregate stiffness) could correlate well with the ASTM C666 test. The proposed approach in this Phase II study can be used to ascertain whether such multivariate correlations exist using the well-established multivariate statistical analysis approaches.

The multivariate regression analyses can be conducted on the numerical results or on the pass/fail outcomes of each test. The non-numeric regression analysis in this case would be a multivariate logistic regression analysis. The parameters in a logistic regression could be numerical (e.g., percent loss in the LA abrasion test) or categorical (e.g., pass/fail, high/low/average, good/bad, democrat/republican/independent). Logistic regressions have been routinely used in medical (and biomedical) applications to evaluate the impact of different drugs or treatments on patients (disease/no disease). However, more recently, many researchers have used the logistic regression tool in civil engineering applications. These include analysis of pavement data (by Haider et al.[(2)]), slope stability (by Lee et al.[(3)]), soil liquefaction (by Lai et al.[(4)]), rock fill flow (by Chen et al.[(5)]), and contaminant source characterization (by Liu et al.[(6)]).

An important parameter in evaluating different tests is the reproducibility and repeatability of results from different test facilities and operators. Some aggregate tests have larger coefficients of variation, which could negatively impact the confidence levels in the predicted outcomes. Therefore, it is important that such information, which can be derived from the Wisconsin aggregate database, be included in the analyses.

There are many comparative aggregate tests in the literature, and many researchers have reported results on different tests; however, there is limited information correlating various tests with actual field performance. There are some works relating tests to D-Cracking in pavements, but few correlate the significance of each test to the long-term field performance. For example, although Weyers et al. [(1)] and others base their test recommendations on the goal of increasing durability in the field, field correlations are usually not available. This apparent discrepancy is mostly due to the lack of field data. Therefore, any analyses of the test results, regardless of how extensive the testing program may be, cannot be used to assert that one or more tests is a better indicator of field performance. The important factor that can be derived from comparative analyses of tests data is establishing whether the test results for various aggregate sources and types are related or they are independent of each other. If the outcomes of a new test are not correlated with one or more results from other tests, then that test is measuring something different and new, which may or may not be relevant to durability in the field. For example, if Micro-Deval tests turn out to be statistically unrelated to the other standard tests, then the Micro-Deval test is measuring something new and different that is not available from other tests. Such a finding would be very valuable and justify the requirement for the new test until correlations with field performance can be established.

The Phase I study was tasked with developing a test protocol for coarse aggregate durability. Laboratory tests of a variety of Wisconsin aggregates were performed using traditional WisDOT tests and newer tests such as Micro-Deval. The Phase I study recommended inclusion of the Micro-Deval test for measuring abrasion resistance, stating the LA abrasion and impact test is more suited as a measure of aggregate strength.

The testing protocols proposed in the Phase I study included both "bound" and "unbound" applications of aggregates, in which bound aggregates are constrained within either a Portland cement or asphalt matrix. A total of 69 natural aggregate samples (from 48 quarries and 22 pits) as well as four recycled/reclaimed aggregate samples were tested in Phase I. Tests performed included the following:

Table 1-1 Tests performed in the Phase I aggregate study [1]

Aggregate Material	Crushed Stone and Gravel	Recycled Concrete Aggregate	Blast Furnace Slag	Recycled Asphalt Pavement
Lightweight Pieces in Aggregate (ASTM C 123-98)	X			
Vacuum Saturated Specific Gravity and Absorption (Modified ASTM C 127)	X	X	X	
Sodium Sulfate Soundness (ASTM C 88)	X	X	X	
Frost Resistance of Aggregates in Concrete (ASTM C 666)	X	X	X	
Unconfined Freezing and Thawing (CSA A23.2-24A)	X	X	X	
Micro-Deval Abrasion (AASHTO TP 58)	X	X	X	
L.A. Abrasion (ASTM C 131-01)	X	X	X	
Aggregate Crushing Value (British Standard 813 – Part 3)	X	X	X	
Compressive Strength of Cylindrical Concrete Specimens (ASTM C 39)	X	X	X	
Resistance of Compacted Asphalt to Moisture Induced Damage (AASHTO T 283)				X

Weyers et al. (Phase I) suggested that aggregate testing requirements can be reduced by using a limit of 2% for the vacuum-saturated absorption (VSA) test. According to the authors, VSA results of less than 2% will meet acceptance criteria for LA abrasion, Micro-Deval, unconfined freeze-thaw, and confined freeze-thaw tests.

Weyers et al. further recommended that WisDOT specifications be modified to reflect their proposed test protocols for applications involving unbound aggregates, aggregates used in Portland cement concretes, and bituminous aggregates. All three protocols (Figure 1-1) included VSA (limit of 2%), LA abrasion (limit of 50%), Micro-Deval (limit of 25%), unconfined freeze/thaw test (limit of 15%), and percent lightweight aggregates (limit of 5%). A basis for the choice of limits specified was not clearly defined. As will be discussed later, the proposed limit of 50% for the LA abrasion and impact test is only exceeded by 0.4% of all aggregates in the Wisconsin database.

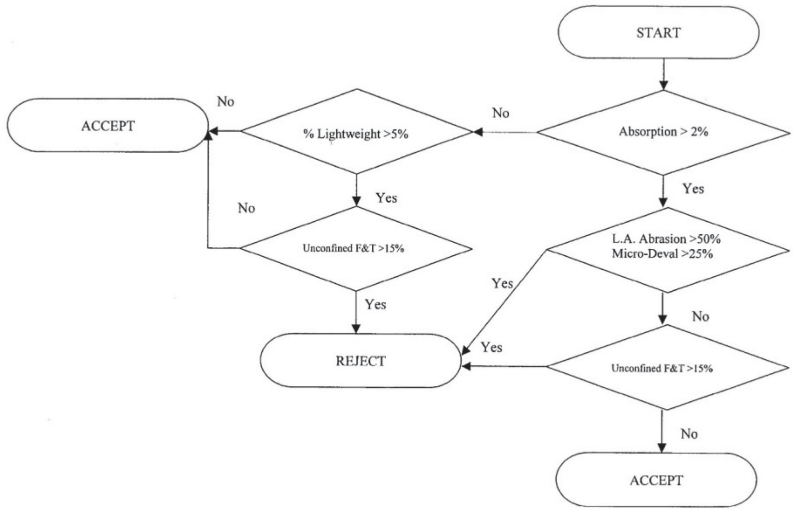


Figure 1 – Aggregate Durability Testing Flowchart for Unbound Aggregate

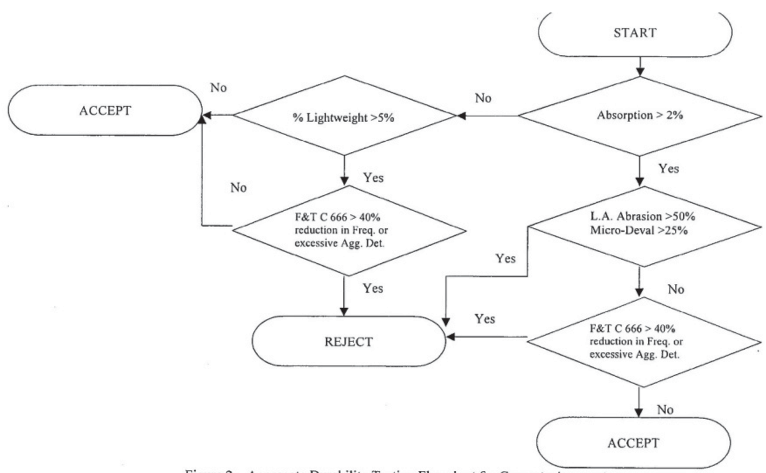


Figure 2 – Aggregate Durability Testing Flowchart for Concrete Aggregates

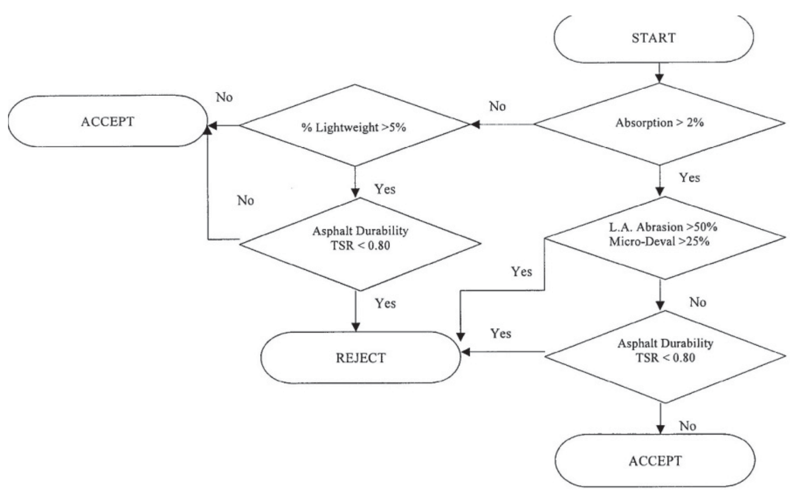


Figure 3 – Aggregate Durability Testing Flowchart for Bituminous Aggregates

Figure 1-1 Test protocols proposed in Phase I study by Weyers et al. [(1)]

1.2 Objectives and Scope

As sources of quality aggregates dwindle and new recycled/reclaimed aggregates are introduced, it is important that the quality of aggregates used in construction be assessed and controlled through appropriate testing. There are a number of aggregate tests that have been performed routinely on all aggregate sources in Wisconsin for decades. This project aims to:

1) Perform a literature search, acquire publications related to aggregate testing, and summarize/organize the data into an EndNote database.
2) Based on analyses of the Wisconsin aggregate test database and the results of the Phase I study, assess whether the outcomes of the Micro-Deval and the unconfined freeze/thaw tests statistically correlate with current standard aggregate tests that are routinely performed by WisDOT.
3) Determine the statistical relationships between the existing standard tests and the Micro-Deval test, if a reasonably accurate relationship can be developed. Assess the implications of some proposed test threshold levels on the test outcomes from various aggregate sources.
4) Provide statistical information on the various results included in the Wisconsin database of aggregate tests. This includes determining best fit statistical distributions to individual test results, reporting test results corresponding with various percentile levels, and determining statistical copulas needed for performing Monte Carlo simulations.
5) Perform aggregate tests on twelve marginal or poor Wisconsin aggregate samples, and assess whether the developed relationships apply to such aggregates.

6) Although not a part of the original scope of work for this project, the research team performed high-resolution x-ray computed tomography (CT) scans of selected aggregates to observe effects of unconfined freeze/thaw and sodium sulfate soundness tests on the internal void structures in aggregate samples. Three-dimensional images of the internal structure of the virgin aggregates and those subjected to freeze/thaw and sodium sulfate soundness were performed. Tests were conducted at the Argonne National Laboratory's Advanced Photon Source (APS) facility near Chicago, Illinois.

CHAPTER 2

LITERATURE REVIEW

2.1 Micro-Deval Testing

Developed in France in the 1960s [11], the Micro-Deval test indicates resistance to abrasion among aggregate particles and between aggregate particles and steel balls in the presence of water. The Micro-Deval test has become the AASHTO Standard TP58-00, “Standard Test Method for Resistance of Coarse Aggregates to Degradation by Abrasion in the Micro-Deval Apparatus.”

Some researchers [17] have reported that the Los Angeles (LA) abrasion test is not a good indicator of quality of HMA aggregates, because of the high distances that large steel spheres drop onto aggregate samples within the test drum. Therefore, some higher quality aggregates, such as granites, can show higher LA abrasion losses, even though they may perform well in the field. Senior and Rogers [15] recommended using the Micro-Deval test in conjunction with petrographic analysis for granular bases. The authors recommended Micro-Deval and the unconfined freeze/thaw test for Portland cement concrete pavements and the unconfined freeze/thaw and polished stone value (PSV) test for HMA surface courses.

Hossain et al.[10] performed a study on the use of the Micro-Deval test for assessing the durability of Virginia aggregates. Ten aggregate sources with known performance histories were evaluated. The researchers concluded that the Micro-Deval test showed a “very high potential in evaluating aggregate durability with higher precision and accuracy than conventional tests such as the magnesium sulfate or the Los Angeles abrasion tests.” They reported that Micro-Deval could predict field performance 80% of the time. They further suggested possibility of replacing the soundness tests or the freeze/thaw tests with the Micro-Deval test.

Several researchers have proposed threshold loss limits for the Micro-Deval test. Rogers et al.[11] recommended a Micro-Deval threshold limit of 20%. White et al. [13] recommend that the Micro-Deval and magnesium sulfate soundness tests be used for aggregates in HMA with loss limits of 15 and 20 percent, respectively. The South Carolina DOT [24] evaluated 23 local aggregate sources using the Micro-Deval and other tests, and their study recommended a 17% Micro-Deval limit in addition to their existing tests. The Colorado DOT [25] has specified a Micro-Deval limit of 18% for HMA. Cooley and James [14] showed that the 18% Micro-Deval result was at the 76 percentile level in their dataset. Rogers et al. [11] recommended a Micro-Deval threshold limit of 25% for use in Portland cement concrete and asphaltic concrete pavements. Tarefder et al. [20] further recommended that a Micro-Deval loss limit of 25% be used in Oklahoma. Lane et al. [16] recommended different Micro-Deval loss limits for HMA applications based on geological and mineralogical characteristics of rocks, and based on application as base or wearing course.

In addition, Hudec and Boateng[12] related Micro-Deval and magnesium sulfate soundness (MSS) tests to aggregate petrography. They reported that higher shale or chert resulted in higher losses in the two tests. In NCHRP 4-19 project (White et al.[13]), researchers recommended that the Micro-Deval test in conjunction with magnesium sulfate soundness test be used in lieu of the LA abrasion test for assessing the potential for raveling, pop-outs, and potholing in pavements.

Cooley and James [14] studied the applicability of Micro-Deval tests on aggregates in the southeastern United States. Seventy-two aggregate sources from eight southeastern states were tested, including good, fair, and poor aggregates as reported by each contributing state. The researchers did not find a relationship between LA abrasion and Micro-Deval results, and large differences in Micro-Deval results were noted within the same performance category.

Cooley and James [14]also concluded that the Micro-Deval test was measuring a different characteristic, because Micro-Deval results were not correlated with LA abrasion or the sodium sulfate soundness tests. They reported mixed results when trying to relate Micro-Deval test results with reported aggregate performance (good, fair, and poor). Cooley and James [14] provided single parameter comparisons between Micro-Deval results and sodium sulfate soundness and LA abrasion tests, and showed lack of correlation (in fact very poor correlation) between the pairs. They further concluded that the aggregate's mineralogical type affects the Micro-Deval results.

Rogers et al. [11] reported on the use of Micro-Deval tests for evaluating fine aggregates used in concrete and asphalt. They reported significant correlation between Micro-Deval and magnesium sulfate soundness and absorption tests for fine aggregates. Senior and Rogers [11] of the Ontario Ministry of Transport discussed laboratory tests for coarse aggregate assessments in Ontario, Canada. They reported,

> "The likely performance of aggregates in granular base is best measured by the Micro-Deval test and water absorption. In the authors' opinion, the quality of Portland cement concrete aggregates is best measured by the Micro-Deval test, water absorption, and unconfined freezing and thawing. The quality of asphaltic concrete aggregates is best measured by the Micro-Deval test, polished stone value test, and unconfined freezing and thawing test."

Senior and Rogers [11] report similarities between Micro-Deval and magnesium sulfate soundness test results; however, they believe that Micro-Deval has greater precision, reporting a correlation coefficient of 0.85 between the two parameters for 106 samples tested. In Figure 2-1, Senior and Rogers present the relationship between Micro-Deval and absorption granular base aggregates considered to be good, fair, and poor.

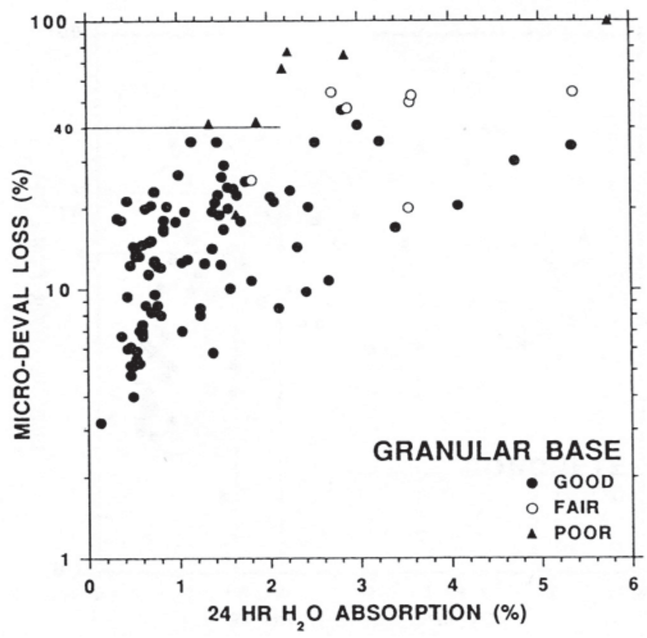


Figure 2-1 Micro-Deval versus absorption for good, fair, and poor aggregates (11)

Rangaraju and Edlinski (18) tested 23 different aggregate sources and found good correlations between magnesium sulfate and sodium sulfate soundness, although the correlations decrease significantly for the results of Micro-Deval and LA abrasion tests. Figure 2-2 shows the correlation between sodium sulfate and magnesium sulfate soundness.

Rangaraju and Edlinski (18) found different results for the Micro-Deval test when the aggregate gradation was changed. AASHTO T 327 specifies three different gradations that can be used for the Micro-Deval test, and results for the same aggregate vary depending on the gradation used during the test. Figure 2-3 shows results for the Micro-Deval test on 23 different aggregates with three different gradations allowed by the AASHTO T 327 standard, which includes the MD-A, MD-B, and MD-C gradations.

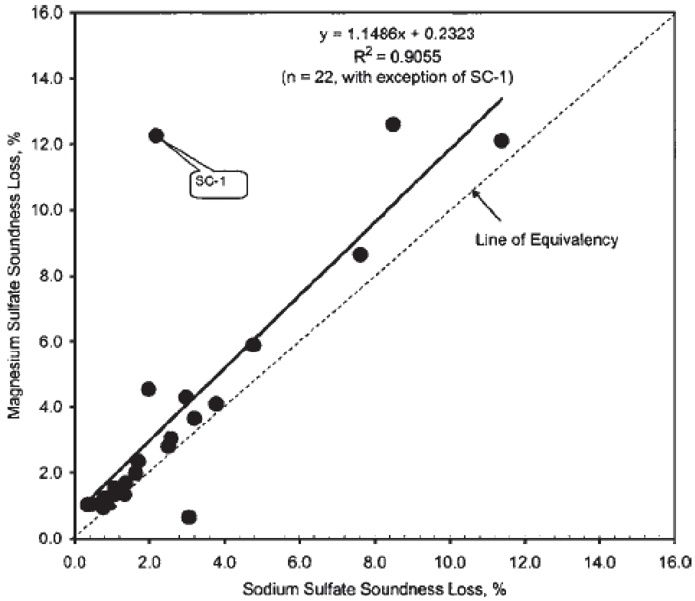


Figure 2-2 Relationship between sodium sulfate and magnesium sulfate soundness tests [18]

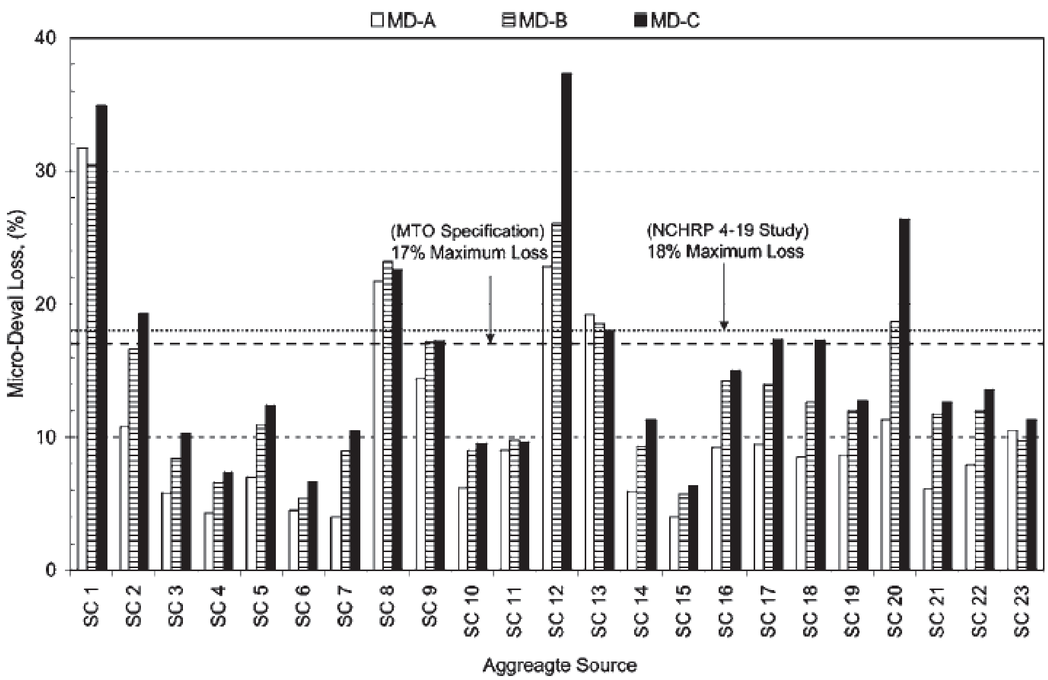


Figure 2-3 Micro-Deval loss for aggregate with different gradations [18]

According to Rangaraju and Edlinski [18], US transportation agencies use an LA abrasion threshold of between 30% and 60%, and a sodium sulfate soundness threshold of up to 15%. Using pass-fail limits (Micro-Deval ≤ 18%, LA Abrasion ≤ 40% and sodium sulfate ≤ 12%), Coelho et al. [19] found good agreement between Micro-Deval and Sodium Sulfate tests (pass/fail agreement = 92.9%). However, pass/fail agreements between Micro-Deval/LA abrasion and sodium sulfate/LA abrasion were not as strong (pass/fail agreement = 85.2% and 84% respectively). Figure 2-4 shows the relationship between LA abrasion and Micro-Deval tests [19].

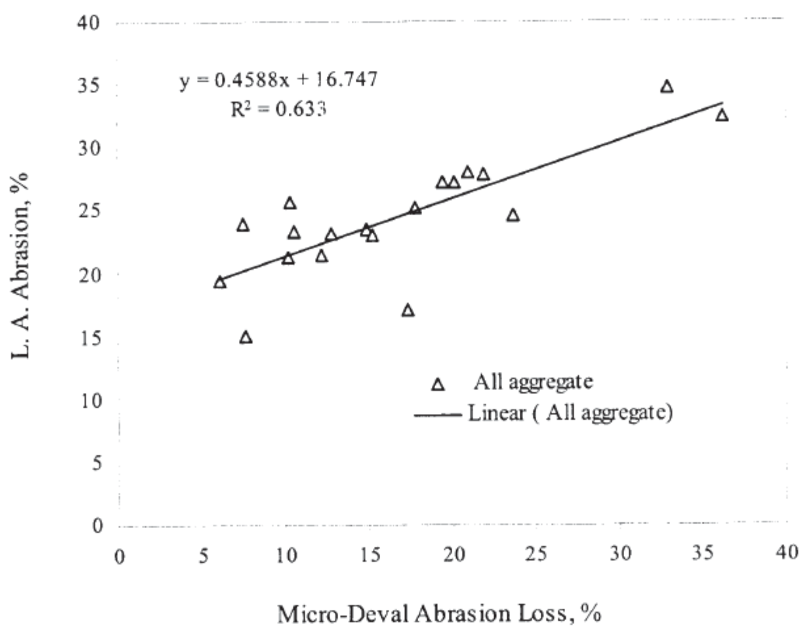


Figure 2-4 Correlation between the LA Abrasion test and Micro-Deval tests [19]

The authors concluded that the field performance can be better represented by the Micro-Deval test because it indicates differences between good and poor aggregates, while such differences are not noticeable in the LA abrasion test results. Correlation between the Micro-Deval and freeze/thaw tests was reported to be very poor.

Hossain et al. [10] tested aggregates selected from nine different Virginia DOT districts with different performance levels. The authors concluded the Micro-Deval test can correctly characterize good/poor aggregate performance on the order of 70% of the time for the coarse aggregate and 80% of the time for the fine aggregate, and they reported that the Micro-Deval test had a higher accuracy for assessing the durability of aggregates than the LA abrasion or magnesium sulfate soundness. Hossain et al. [10] also reported that "coarse aggregates with a good performance rating had [Micro-Deval] loss values of less than 15% and should be suitable for use in all applications." However, they cautioned that Micro-Deval should supplement, not replace, other aggregate tests until more experience and data are available.

A number of researchers [13, 14, 15, 8] have suggested using the Micro-Deval test as an aggregate qualification test; however, Hunt [7] suggests that Micro-Deval was not any better than the LA abrasion test for evaluating resistance to studded tires. Jayawickrama et al. [8] report that Micro-Deval results are better correlated with magnesium sulfate soundness test results when absorption values are also considered.

Additionally, 21 of the 23 aggregates tested by Rangaraju and Edlinski [19] were granite or granitic-gneiss, one was marine limestone, and the other marble schist. Their tests were performed on three different gradations of the aggregates. An R^2 of 0.3 was reported between LA abrasion and magnesium sulfate soundness. Also, Micro-Deval did not correlate with sodium or magnesium sulfate soundness, while correlation existed between sodium and magnesium soundness tests.

Lang et al. [9] recommended using the Micro-Deval test to identify good-performing aggregates (but not to reject aggregates). Tarefder et al. [20] performed tests on 18 limestone and sandstone aggregate sources from Oklahoma, and concluded that the LA abrasion test was not adequate for predicting field performance. They considered Micro-Deval to be a satisfactory indicator of field performance.

Rogers and Senior [21] recommended a combined Micro-Deval/unconfined freeze/thaw tests of coarse aggregates for predicting aggregate performance in concrete. They argued that there are many aggregates that are unsatisfactory. but perform adequately in the LA abrasion test. Rogers and Senior [21] suggest that abrasion tests should be done on wet aggregates; however, the

LA abrasion test cannot be done on wet aggregates because of the difficulty in cleaning the container.

The NCHRP report 453 [22] recommended the use of Micro-Deval as a measure of aggregate toughness and abrasion resistance and the magnesium sulfate test as a measure of aggregate durability. The NCHRP report suggests loss limits for Micro-Deval and other tests based on traffic conditions (ESAL count), moisture (high, low), and temperature (freezing, non-Freezing) (Table 2-1 below).

The NCHRP report 557 [13] is another national study that focuses on aggregate tests used for Hot-Mix-Asphalt (HMA) for pavements. The authors reported that Micro-Deval and magnesium sulfate soundness "appear reasonably predictive of HMA performance." They recommended Micro-Deval and magnesium sulfate soundness limits of 15% and 20%, respectively, for HMA applications, and recommended that these two tests be performed in all climates and for all materials.

Table 2-1 Proposed aggregate test threshold levels, by Saeed et al. [22]

TABLE 6.20 Recommended tests and test parameters for assessment of aggregate performance potential

TESTS	Traffic	High		Medium		High		Low	Medium		Low		
	Moisture	High	Low	High	Low	High	Low	High	High	Low	Low	High	Low
	Temperature	F	F	F	F	NF	NF	F	NF	NF	F	NF	NF
Screening Tests [a]													
	Gradation, Cu	≥ 6			≥ 6				≥ 2				≥ 2
	Max. Aggregate Size	≥ 3/4"			≥ 3/4"				≥ 3/4"				≥ 3/4"
	Minus #200, #	≤ 5			≤ 8				≤ 10				0 ≤ # ≤ 12
	Atterberg Limits [b]	Nonplastic			Nonplastic				Nonplastic				Nonplastic
	Uncompacted Voids, Uc	< 35			< 45				< 55				Uc < 65
	Flat and elongated 5:1m	< 0.10			< 0.10				< 0.32				< 0.32
Toughness/Abrasion													
	Micro-Deval, MD	≤ 5			≤ 15				≤ 30				≤ 45
Durability													
	Sulfate Soundness, S	≤ 13			≤ 30				≤ 30				≤ 45
Frost Susceptibility [c]													
	Tube Suction Test, DCV	≤ 7			≤ 10				≤ 15				≤ 20
	F - Category	F-1			≥ F-2				≥ F-2				≥ F-3
Shear Strength [d]													
	Std. dry, σc=5psi, σd	≥ 100			≥ 60				≥ 40		≥ 25		Not Required
	Std. wet, σc=15psi, σd	≥ 180			≥ 135				≥ 90		≥ 60		
	Rep. dry, σc=15psi, σd	≥ 180			≥ 160				≥ 130		≥ 90		
	Rep. wet, σc=15psi, σd	≥ 180			≥ 160				≥ 125		≥ 60		
Stiffness													
	Res. Modulus, M_R	≥ 60 ksi			≥ 40 ksi				≥ 32 ksi		≥ 25 ksi		

a. Screening tests should also include specific gravity and moisture-density relationship tests
b. Most state DOTs allow some plastic fines in their base/subbase layers; all test samples were nonplastic
c. Frost susceptibility tests are not required in non-frost areas
d. Triaxial tests are optional for the low traffic category

Cooley et al. [23] reports on a study of aggregates in the southeastern United States. The authors tested aggregates from Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, and Tennessee. Two of the six aggregates characterized as “poor” had Micro-Deval results that were less than 6%. The average Micro-Deval loss for all “poor” aggregates was 17.1%. Aggregates that were characterized as “good” had average LA abrasion results of 28% with a standard deviation of 11%. This indicates a wide range of Micro-Deval and LA abrasion results for both “fair” and “poor” aggregates. The authors concluded that Micro-Deval had “mixed results” compared with the performance histories reported by various states.

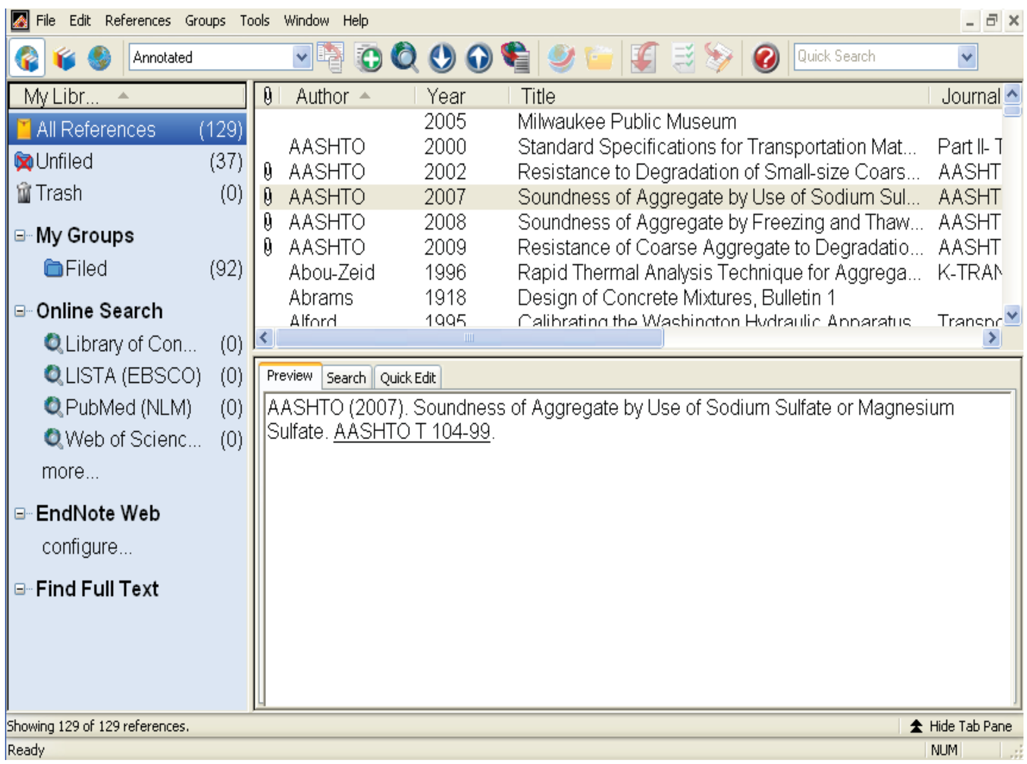
Cuelho et al. [19] compared Micro-Deval, LA abrasion, sodium sulfate and magnesium sulfate test results and performed linear regression analyses. They recommended that the Micro-Deval test be used with the support of another test when Micro-Deval results fall between 18% and 27%.

Woodhouse [26] conducted a multi-state coarse aggregate freeze/thaw comparison. Four coarse aggregate samples from limestone/dolomite sources in Michigan were sent to five different Midwestern state DOTs (Illinois, Kansas, Michigan, Minnesota and Ohio). The DOTs were asked to test the aggregates for freeze/thaw durability in pavements based on their own established tests and criteria. Two aggregate sources received unanimous pass or fail verdicts, while the other two sources received mixed verdicts.

Fowler et al. [29] performed a comprehensive study on predicting coarse aggregate performance using Micro-Deval and other tests. The results of that substantial study are further analyzed in this study (see Chapter 4).

2.2 Literature Database

The research team conducted a comprehensive literature search for relevant papers, technical reports, and other publications pertaining to the durability testing of aggregates. In most cases, electronic copies of the papers and reports were obtained. A database of relevant documents, including journal papers, research reports, and test standards, were entered into an End Note® database. Figures 2-5 show screen images of the End Note database. A bibliography of papers and other documents catalogued in the database (total of 129 documents) is listed in Appendix A.



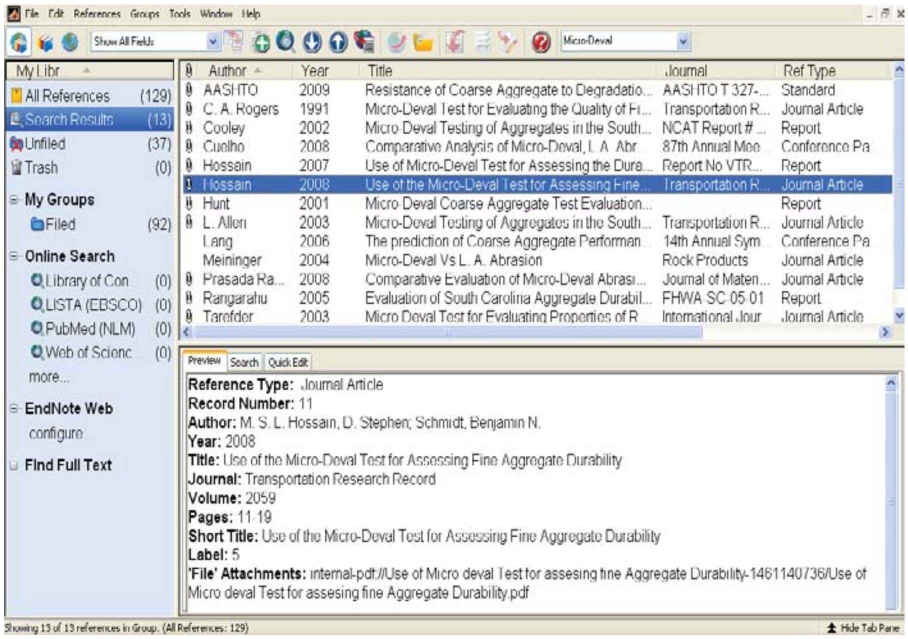


Figure 2-5 End Note screen showing references collected on aggregate testing

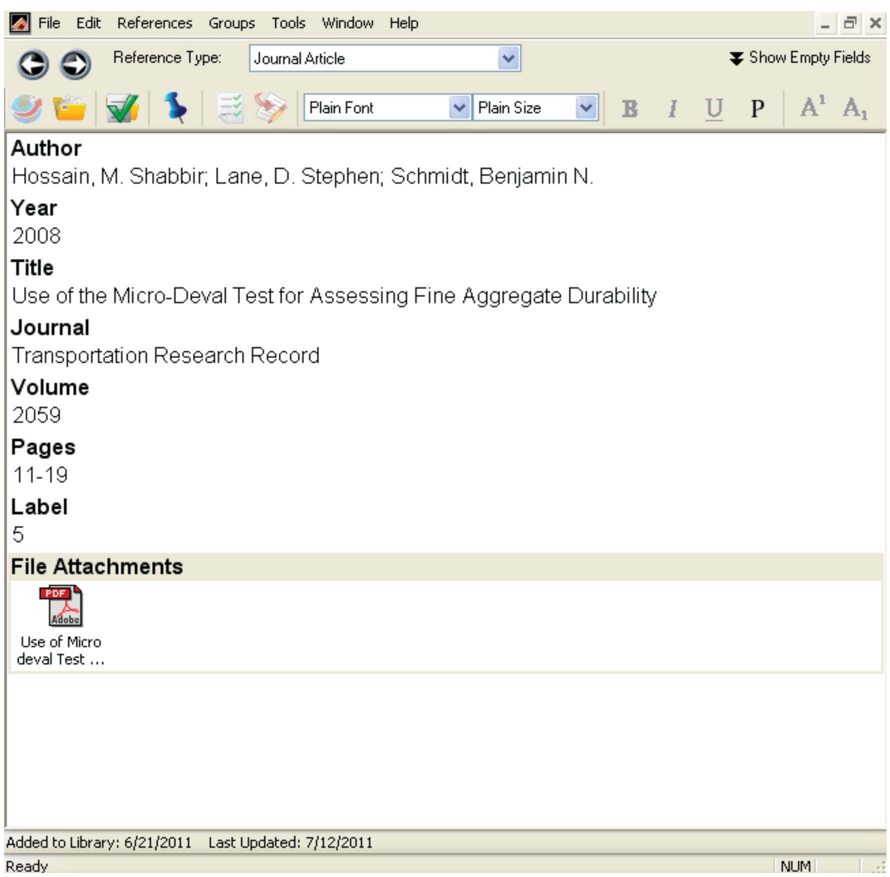


Figure 2-6 End Note screen showing information on a publication

CHAPTER 3

STATISTICAL ANALYSIS OF WISCONSIN DATABASE OF AGGREGATE TESTS

3.1 Basic Statistics

An electronic database of historical aggregate test results was obtained from the Wisconsin Department of Transportation (WisDOT). The results represented all aggregate tests performed between years 2000 and 2009. A total of 2,052 sets of aggregate test results were included in the database; of the total number of datasets, 1,019 were identified as aggregates acquired from pits and 1,031 were obtained from quarries. The tests reported included LA abrasion, sodium sulfate soundness, unconfined freeze/thaw, absorption (fine aggregates), absorption (coarse aggregates), specific gravity (fine aggregates), and specific gravity (coarse aggregates).

The database information is presented in Appendix A. Not all datasets include all of the test results—some data records were left blank, presumably because those specific tests were not performed. On the other hand, some data records had a “0” in them. Initially, the research team analyzed the data assuming that the zeroes were actual data; however, the analysis of data with and without inclusion of zeroes indicates that test results showing “0” were likely not performed.

Tables 3-1 through 3-3 show basic statistics on the Wisconsin database test records for all aggregates (from pits and quarries), aggregates from pits, and aggregates from quarries.

Table 3-1 Basic statistics on the database results (all aggregates (pits and quarries)

	LAA	SSS	F&T	ABS (fine)	SG (fine)	ABS (coarse)	SG (coarse)
Mean	29.34	3.36	1.57	0.76	2.66	1.71	2.66
Median	29.14	2.00	0.00	0.75	2.66	1.50	2.66
Standard Deviation	8.257	4.399	4.553	0.017	0.033	0.024	0.002
Minimum	10.90	0.00	0.00	0.15	2.58	0.29	1.28
Maximum	56.70	46.82	57.71	1.95	2.79	9.14	3.19
Count	1700	2051	2036	314	314	1348	1348

Table 3-2 Basic statistics on the database results (aggregates from pits only)

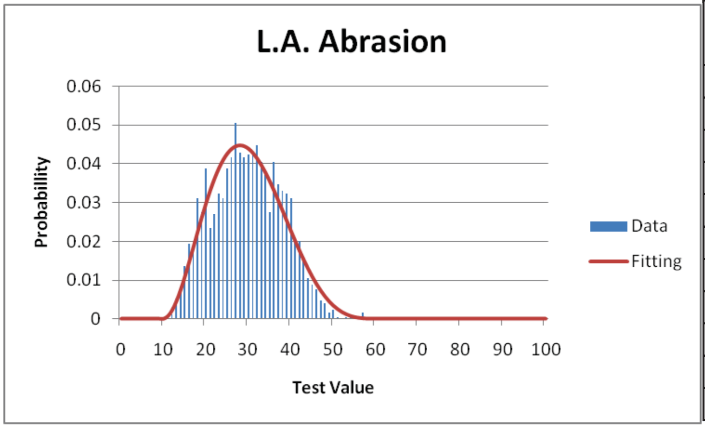
	LAA	SSS	F&T	ABS (fine)	SG (fine)	ABS (coarse)	SG (coarse)
Mean	25.17	2.48	0.53	0.77	2.66	1.35	2.69
Median	25.02	1.47	0.00	0.76	2.66	1.25	2.69
Standard Deviation	6.720	3.881	3.472	0.018	0.033	0.022	0.003
Minimum	11.46	0.00	0.00	0.15	2.58	0.40	2.19
Maximum	56.70	46.82	53.37	1.93	2.79	4.21	2.85
Count	722	1021	1021	277	277	590	590

Table 3-3 Basic statistics on the database results (aggregates from quarries only)

	LAA	SSS	F&T	ABS (fine)	SG (fine)	ABS (coarse)	SG (coarse)
Mean	32.42	4.22	2.62	0.73	2.65	1.99	2.64
Median	32.99	2.70	0.47	0.64	2.65	2.03	2.62
Standard Deviation	7.928	4.700	5.225	0.055	0.028	0.035	0.004
Minimum	10.90	0.00	0.00	0.28	2.60	0.29	1.28
Maximum	56.50	33.05	57.71	1.95	2.72	9.14	3.19
Count	978	1030	1015	37	37	758	758

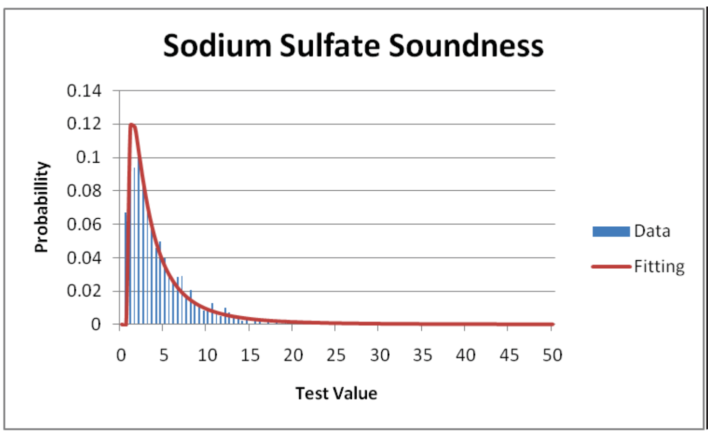
Figure 3-1 shows a histogram of all LA abrasion results in the database. A best-fit statistical distribution was fit to the histogram data. The percentiles for the actual data and the statistical distribution curve are also shown in Figure 3-1. It should be noted that an LA abrasion loss of 50% corresponds with the 99.6 percentile; therefore, if a threshold loss level of 50% is selected, only 0.4% of Wisconsin aggregates would fail such a test.

Similar analysis results for other aggregate tests in the database are shown in Figures 3-2 through 3-9. It should be noted that not all records had results from all tests; some test results were left blank, but others had zeros in them (this was the case with the freeze/thaw and sodium sulfate soundness results). In such cases, the analyses were performed in two ways, one excluding the zeroes (assuming that the tests were not performed), and the other including zeroes as valid results. The histograms indicate that the results excluding the zero records have much more reasonable distributions. Therefore, the data analyzed without the zero records are used in the subsequent discussions in this report.



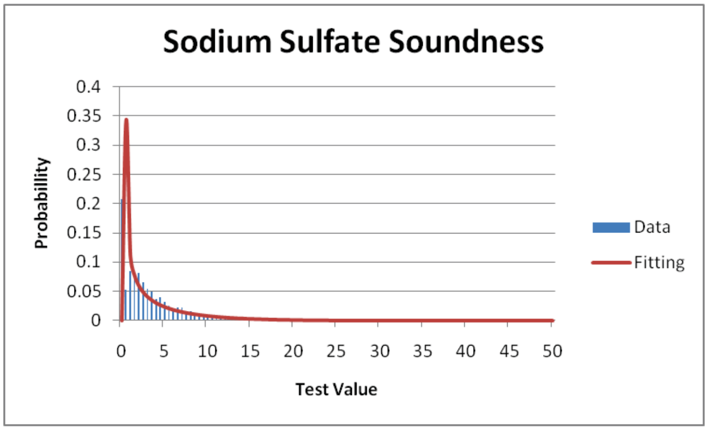
Percentile	Data	Distribution Fitting
0%	10.90	10.13
10%	18.14	18.70
20%	21.59	21.79
30%	24.63	24.29
40%	26.84	26.58
50%	29.14	28.82
60%	31.61	31.13
70%	34.01	33.65
80%	36.92	36.61
90%	40.03	40.63
100%	56.70	56.46

Figure 3-1 Histogram, distribution fit, and percentiles for the LA abrasion test results in the Wisconsin aggregate database (pits and quarries included)



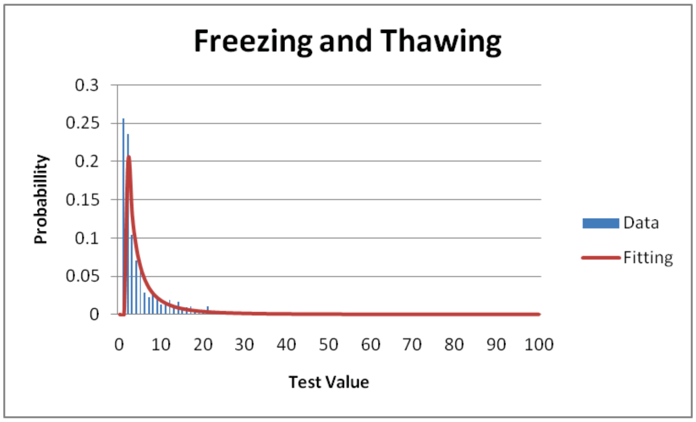
Percentile	Data	Distribution Fitting
0%	0.03	0.06
10%	0.64	0.71
20%	1.10	1.11
30%	1.65	1.54
40%	2.17	2.04
50%	2.81	2.64
60%	3.63	3.43
70%	4.83	4.53
80%	6.47	6.28
90%	9.29	9.88
100%	46.82	121.24

Figure 3-2 Histogram, distribution fit, and percentiles for the sodium sulfate soundness test results in the Wisconsin aggregate database (“0” data not included)



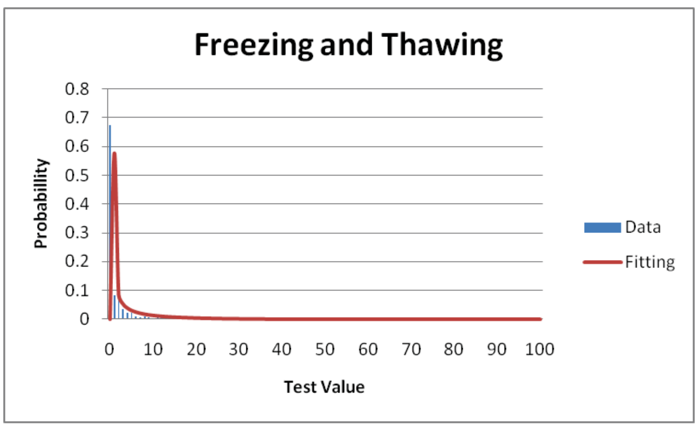
Percentile	Data	Distribution Fitting
0%	0.00	0.00
10%	0.00	0.03
20%	0.00	0.14
30%	0.74	0.36
40%	1.35	0.73
50%	2.00	1.30
60%	2.76	2.12
70%	3.94	3.33
80%	5.43	5.22
90%	8.17	8.62
100%	46.82	33.39

Figure 3-3 Histogram, distribution fit, and percentiles for the sodium sulfate soundness test results in the Wisconsin aggregate database ("0" data included)



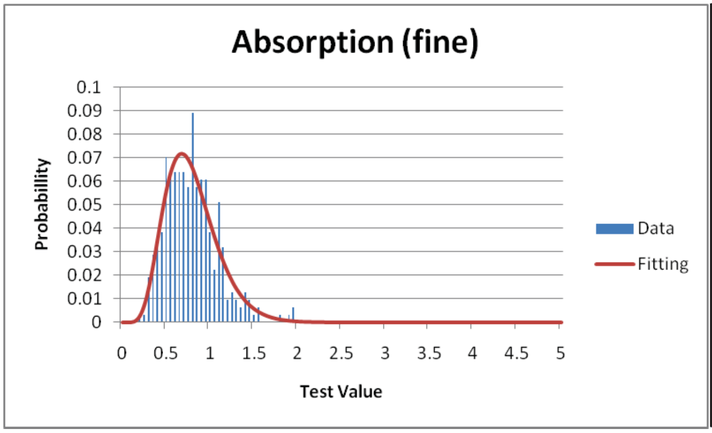
Percentile	Data	Distribution Fitting
0%	0.07	0.02
10%	0.45	0.45
20%	0.72	0.78
30%	1.14	1.17
40%	1.58	1.65
50%	2.10	2.26
60%	3.05	3.12
70%	4.53	4.39
80%	7.45	6.55
90%	13.13	11.40
100%	57.71	246.58

Figure 3-4 Histogram, distribution fit, and percentiles for the unconfined freeze/thaw test results in the Wisconsin aggregate database ("0" data not included)



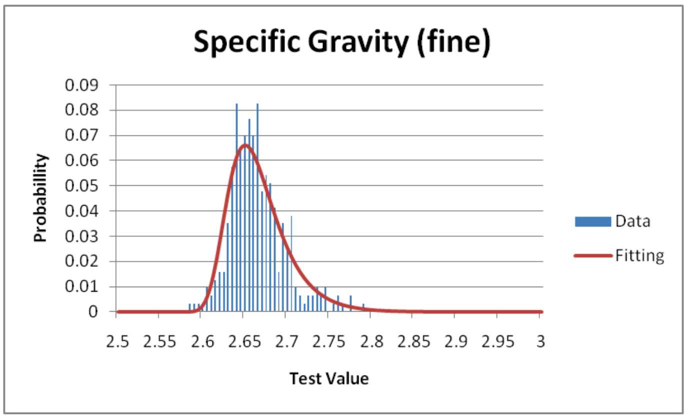
Percentile	Data	Distribution Fitting
0%	0.00	0.00
10%	0.00	0.00
20%	0.00	0.01
30%	0.00	0.04
40%	0.00	0.16
50%	0.00	0.46
60%	0.00	1.15
70%	0.36	2.55
80%	1.50	5.32
90%	4.42	11.34
100%	57.71	50.83

Figure 3-5 Histogram, distribution fit, and percentiles for the unconfined freeze/thaw test results in the Wisconsin aggregate database ("0" data included)



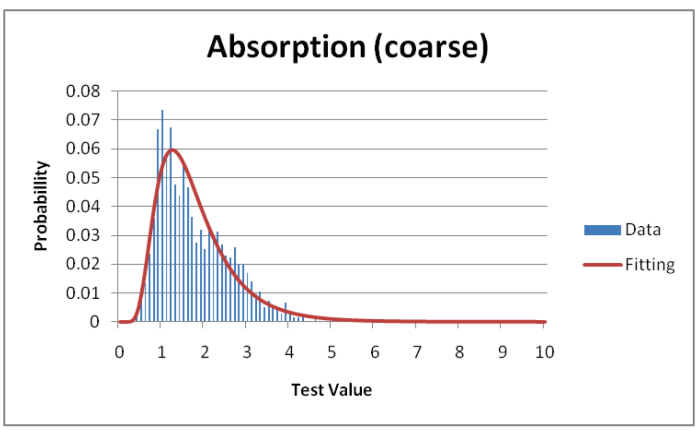
Percentile	Data	Distribution Fitting
0%	0.15	0.00
10%	0.42	0.42
20%	0.50	0.51
30%	0.58	0.58
40%	0.66	0.65
50%	0.75	0.73
60%	0.81	0.80
70%	0.89	0.89
80%	0.99	1.00
90%	1.11	1.16
100%	1.95	4.05

Figure 3-6 Histogram, distribution fit, and percentiles for the absorption test results (fine aggregates) in the Wisconsin aggregate database



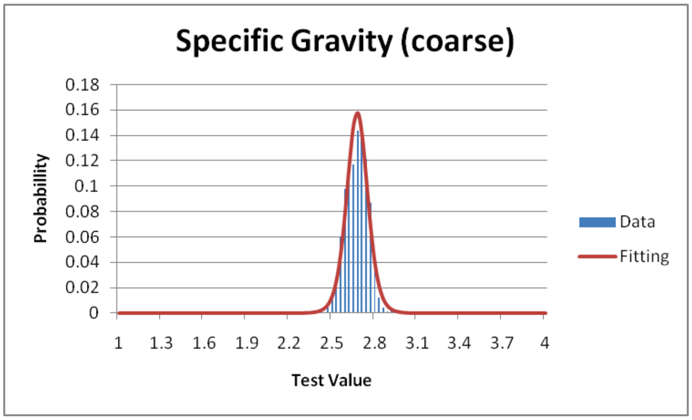
Percentile	Data	Distribution Fitting
0%	2.58	-Infinity
10%	2.63	2.62
20%	2.64	2.63
30%	2.64	2.64
40%	2.65	2.65
50%	2.66	2.66
60%	2.66	2.67
70%	2.67	2.68
80%	2.68	2.69
90%	2.70	2.71
100%	2.79	+Infinity

Figure 3-7 Histogram, distribution fit, and percentiles for the specific gravity test results (fine aggregates) in the Wisconsin aggregate database



Percentile	Data	Distribution Fitting
0%	0.29	0.23
10%	0.82	0.80
20%	0.96	0.99
30%	1.12	1.16
40%	1.30	1.33
50%	1.50	1.51
60%	1.76	1.72
70%	2.09	1.97
80%	2.44	2.31
90%	2.89	2.88
100%	9.14	9.76

Figure 3-8 Histogram, distribution fit, and percentiles for the absorption test results (coarse aggregates) in the Wisconsin aggregate database



Percentile	Data	Distribution Fitting
0%	1.28	-Infinity
10%	2.56	2.56
20%	2.59	2.59
30%	2.61	2.62
40%	2.64	2.64
50%	2.66	2.66
60%	2.68	2.68
70%	2.70	2.70
80%	2.73	2.72
90%	2.76	2.76
100%	3.19	+Infinity

Figure 3-9 Histogram, distribution fit, and percentiles for the specific gravity test results (coarse aggregates) in the Wisconsin aggregate database

The histogram data were fit to a number of standard statistical distributions to find the best-fit distributions for each parameter. The software programs Crystal Ball® and ModelRisk® were used to find the best-fit distributions. Table 3-4 through 3-6 show the curve-fitting of standard distributions to various database parameters. Figure 3-10 shows the typical shapes of various standard distributions [(27)].

Table 3-4 Distributions fit to all data (pits and quarries)

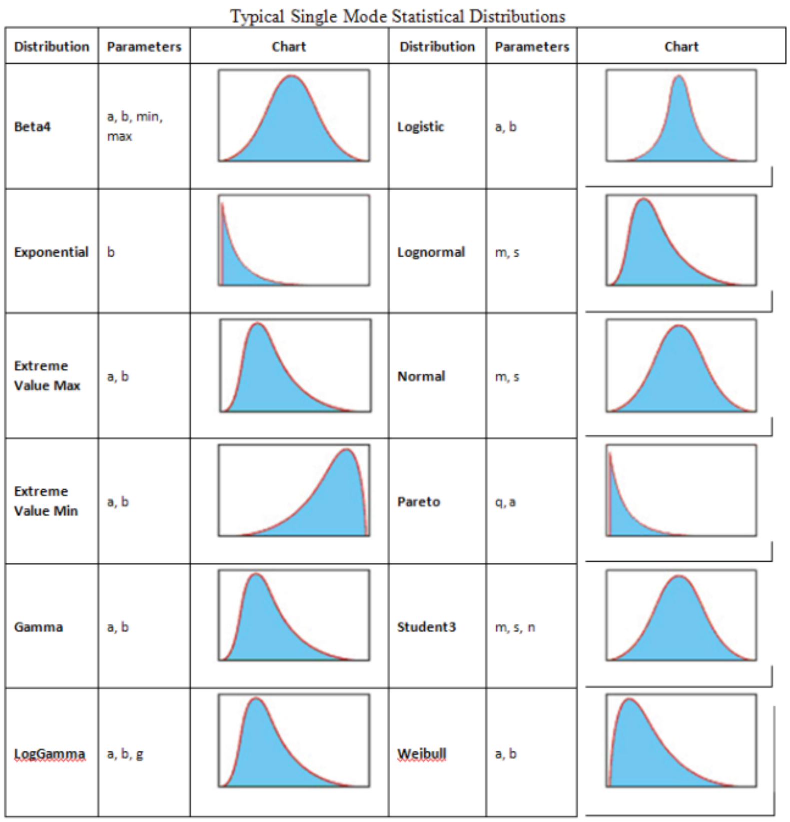
	LAA	SSS	F&T	ABS (fine)	SG (fine)	ABS (coarse)	SG (coarse)
Distribution	Beta4	Beta4	Beta4	Gamma	ExtValueMax	LognormalE	Student3
Parameter 1	3.20918	0.42281	0.20556	6.59810	2.64733	0.41483	2.65935
Parameter 2	5.05103	6.12152	3.22041	0.11575	0.02777	0.50108	0.08267
Parameter 3	9.19484	0.00000	0.00000	N/A	N/A	N/A	9
Parameter 4	60.97145	47.05186	57.73749	N/A	N/A	N/A	N/A

Table 3-5 Distributions fit to all data (pits only)

	LAA	SSS	F&T	ABS (fine)	SG (fine)	ABS (coarse)	SG (coarse)
Distribution	Beta4	Beta4	Kumaraswamy4	Gamma	ExtValueMax	LognormalE	Student3
Parameter 1	3.43865	0.38465	0.10198	6.71248	2.64831	0.23348	2.68875
Parameter 2	11.93649	6.10658	1.46981	0.11452	0.02838	0.36431	0.06174
Parameter 3	10.52229	0.00000	0.00000	N/A	N/A	N/A	4
Parameter 4	75.99033	46.92981	53.51761	N/A	N/A	N/A	N/A

Table 3-6 Distributions fit to all data (pits only)

	LAA	SSS	F&T	ABS (fine)	SG (fine)	ABS (coarse)	SG (coarse)
Distribution	Weibull	Beta4	Beta4	LognormalE	ExtValueMax	Weibull	Student3
Parameter 1	4.67000	0.54662	0.30773	-0.40543	2.64073	2.16449	2.63275
Parameter 2	35.45233	3.93094	4.18017	0.40730	0.02242	2.25157	0.09108
Parameter 3	N/A	0.00000	0.00000	N/A	N/A	N/A	7
Parameter 4	N/A	33.25427	57.76717	N/A	N/A	N/A	N/A



Typical Single Mode Statistical Distributions

Distribution	Parameters	Chart	Distribution	Parameters	Chart
Beta4	a, b, min, max		Logistic	a, b	
Exponential	b		Lognormal	m, s	
Extreme Value Max	a, b		Normal	m, s	
Extreme Value Min	a, b		Pareto	q, a	
Gamma	a, b		Student3	m, s, n	
LogGamma	a, b, g		Weibull	a, b	

Figure 3-10 Statistical distributions used to find best fit distributions [27]

3.2 Copulas

The distributions presented in the previous section can be used to perform statistical simulations; however, these distributions are determined without considering their interdependence. These distributions are not independent of each other and cannot be used as independent parameters in simulations. For example, if the simulation involves picking a sample aggregate test result, an independent set of distributions could provide a very low absorption and a very high Micro-Deval result without considering the likelihood for such an occurrence.

For the purpose of statistical simulations, data are randomly taken from each parameter's distribution. If the parameters involved in the simulations are all independent of each other, then performing large number of simulations (e.g., 10,000) can provide statistical information on the simulation outcomes. When parameters are inter-dependent, a set of copulas must be determined for a representative simulation.

In this research, the database information was used to find the best-fitting standard copula. The Clayton copula was determined to best fit the data based on the analysis using ModelRisk software [27]. Table 3-7 shows the Clayton parameter for all data, pits, and quarries. The order of parameters in this copula was 1) absorption (coarse); 2) LA abrasion; and 3) sodium sulfate soundness. Statistical distributions and copulas can be used to perform Monte Carlo simulations on Wisconsin aggregates (from pits, quarries, or both). Any aggregate qualification requirements can be tested (its impact assessed) using the simulations.

Table 3-7 Copula parameters

	All	Pit	Quarry
Type	Clayton	Clayton	Clayton
Parameter	1.343	0.6016	0.2877

CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Analysis of Phase I Study Data

The following procedure was used to analyze the test database:

1. Import the available data into Excel
2. Eliminate inappropriate data from the entire database
3. Obtain descriptive statistics for every test
4. Plot the distributions of data (examples shown in the following figures)
5. Compare and find the best-fit curves to the data
6. Specify the statistical distributions and their parameters
7. Perform the Monte Carlo simulation for each test
8. Verify the simulation with original data

Three aggregate test datasets were analyzed in this study: 1) Wisconsin data from years 2000–2010; 2) test data on 69 aggregate sources reported in the Phase I study [(1)]; and 3) data used in the Texas study [(29)]. For comparison, the data in the Wisconsin database are grouped into three sets: all (pits and quarries), pits, and quarries. The fitting curves of statistical distributions are determined through the ModelRisk software [(27)], and the Monte Carlo simulation is performed by the Crystal Ball software [(28)].

The Phase I study included tests test on aggregate samples from across Wisconsin. Table 4-1 shows basic statistics for the data reported by Weyers et al. [(1)] for the Micro-Deval test, vacuum-absorption test (ABS), LA abrasion and impact (LAA), aggregate crushing value (ACV), sodium sulfate soundness (SSS), unconfined freeze/thaw (UFT) and percent lightweight test.

Table 4-1 Basic statistics for the Phase I test results (%) (Weyers et al. [1])

	Micro-Deval	ABS	LAA	ACV	SSS	UFT	% Lightweight
Mean	16.70	2.58	27.68	20.47	5.16	6.28	2.80
Median	16.22	2.59	27.70	19.38	3.45	5.90	1.60
Standard Deviation	1.077	0.173	1.279	0.583	0.764	0.431	0.444
Minimum	3.42	0.38	9.89	11.39	0.03	0.90	0.00
Maximum	39.98	5.91	56.88	29.46	31.42	13.90	16.20
Count	58	60	59	57	60	60	60

ABS: Absorption; LAA: LA Abrasion; ACV: Aggregate Crushing Value; SSS: Sodium Sulfate Soundness; UFT: Unconfined Freeze/thaw

Figures 4-1 through 4-2 show histograms and distributions fit to the Phase I study results for various tests.

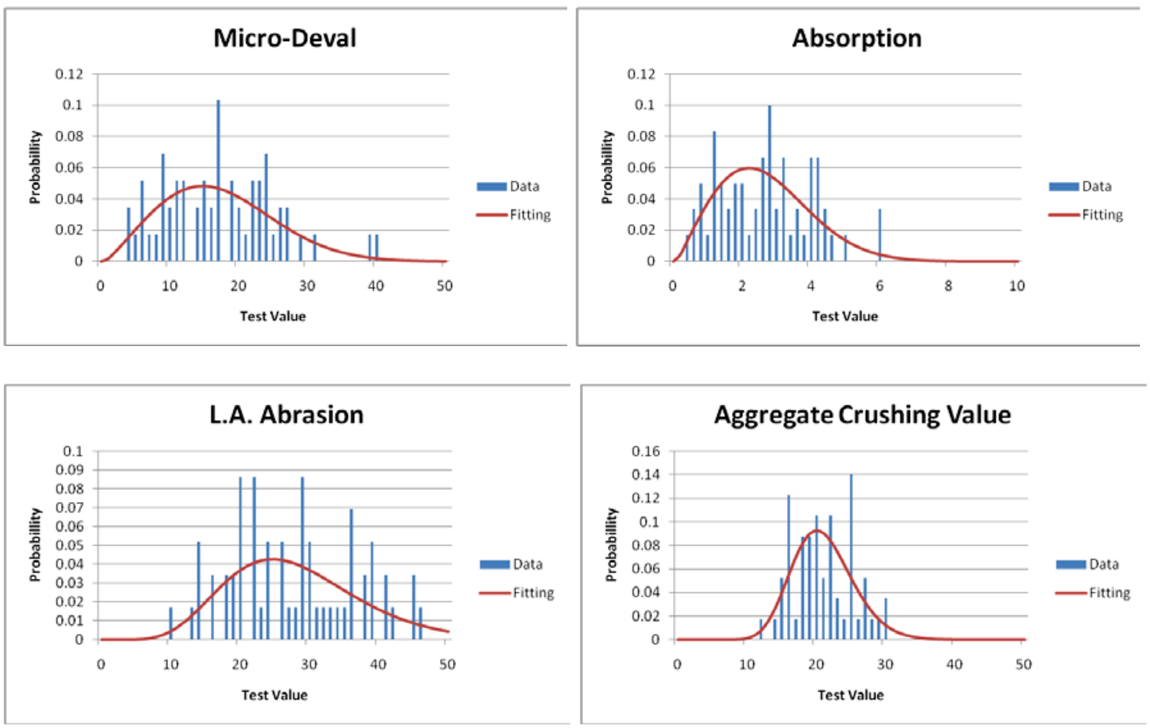


Figure 4-1 Histograms and best-fit distributions for Micro-Deval, absorption, LA abrasion, and aggregate crushing value tests performed in Phase I study

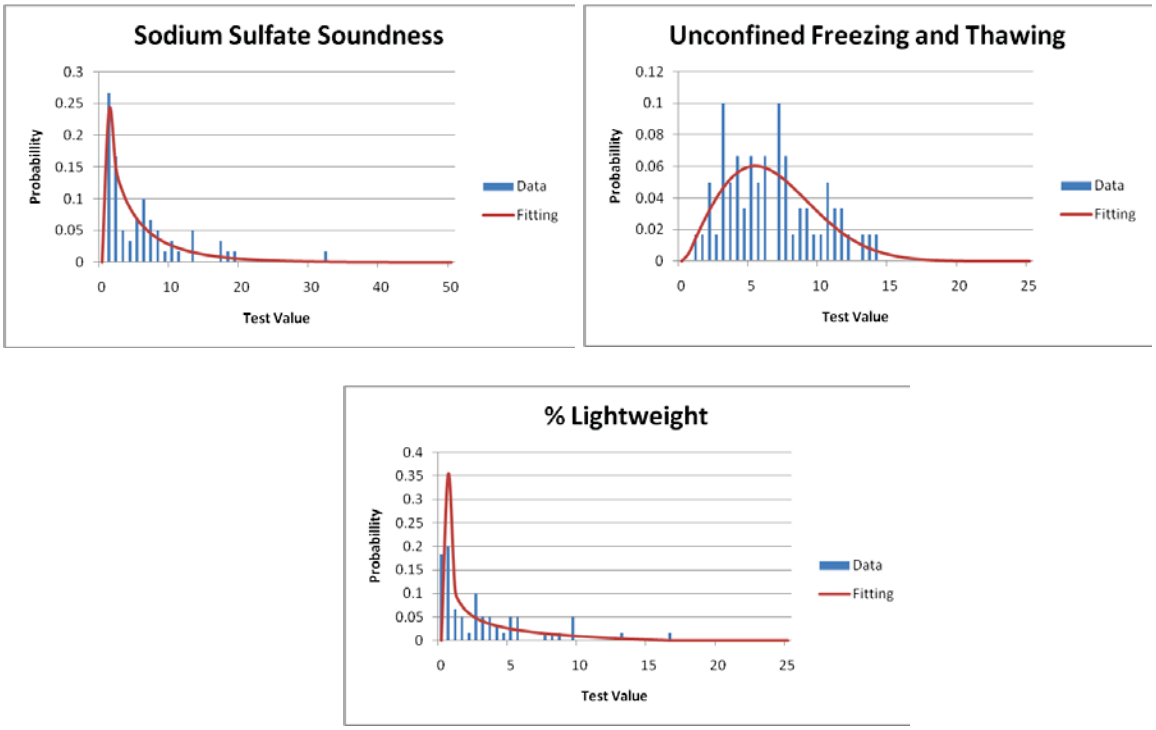


Figure 4-2 Histograms and best-fit distributions for sodium sulfate soundness, unconfined freezing and thawing, and percent lightweight tests performed in Phase I study

Table 4-2 below shows the best-fit distributions and respective parameters determined for each set of test results from the Phase I study. Table 4-3 shows the results of a multi-parameter regression analysis performed on the test data from the Wisconsin database. The intersection of each row and column associated with various tests shows the correlation between the two test results. For these analyses, only records with results from all tests were used. It is clear that the highest correlation exists between absorption and Micro-Deval. The lowest correlations exist between the unconfined freeze/thaw tests and the other tests. It is interesting to note the sodium sulfate soundness and the unconfined freeze/thaw have the least correlation, even though some consider the sodium sulfate test as a rapid test to measure freeze/thaw resistance—this is clearly not the case based on these correlation results.

Table 4-2 Best fit statistical distributions for Phase I study data.

	Micro-Deval	ABS	LAA	ACV	SSS	UFT	% Lightweight
Distribution	Weibull	Weibull	Gamma	Gamma	Weibull	Weibull	Beta4
Parameter 1	2.18080	2.04617	7.84694	21.82044	0.83384	2.00512	0.38799
Parameter 2	18.87918	2.91359	3.52712	0.93828	4.69579	7.10400	1.99750
Parameter 3	N/A	N/A	N/A	N/A	N/A	N/A	0.00000
Parameter 4	N/A	N/A	N/A	N/A	N/A	N/A	16.44726

Table 4-3 Correlations between results of various aggregate tests in the Phase I study

Variables	Micro-Deval	ABS	LAA	SSS	UFT
Micro-Deval	1	0.92709	0.75292	0.74870	0.39333
ABS	0.92709	1	0.75700	0.64853	0.33832
LAA	0.75292	0.75700	1	0.49310	0.32384
SSS	0.74870	0.64853	0.49310	1	0.12991
UFT	0.39333	0.33832	0.32384	0.12991	1

Three sets of logistic regression analyses were also performed on the Wisconsin database records. The logistic regression consisted of a pass/fail outcome for the Micro-Deval test as a function of three or four parameters. Two sets of three-parameter analyses and one set of four-parameters analyses were performed as shown below:

A) Three parameters (1):

   Parameters: Absorption, LA Abrasion, Sodium Sulfate Soundness

B) Three parameters (2):

   Parameters: Absorption, Sodium Sulfate Soundness, Unconfined Freezing and Thawing

C) Four parameters:

   Parameters: Absorption, LA Abrasion, Sodium Sulfate Soundness, Unconfined Freezing and Thawing

The logistic regression analyses were performed to determine whether the pass/fail outcome of the Micro-Deval test can be determined from the other test parameters that

Wisconsin routinely performs. Two three-parameter relationships (A and B) and one four-parameter relationship (C) were developed for various threshold limits for the Micro-Deval test. For example, for a commonly specified Micro-Deval limit of 18%, the following relationship is developed based on the Phase I study results.

$$micro - Deval\ outcome_{18\%-A} = \frac{1}{(1 + e^{-(1993.2-341.45(ABS)-29.68(LAA)-49.455(SSS))})}$$

If the result of the above is greater than 0.5, the outcome is a “pass,” otherwise it is a “fail.”

$$micro - Deval\ outcome_{18\%-B} = \frac{1}{(1 + e^{-(18.62-5.13(ABS)-0.4656(SSS)-0.22527(UFT))})}$$

$$micro - Deval\ outcome_{18\%-C} = \frac{1}{(1 + e^{-(805.1-130.73(ABS)-11.049(LAA)-20.5(SSS)-4.987(UFT))})}$$

Using the above equations, the accuracy of predictions for the outcome of the Micro-Deval test was evaluated. Table 4-4 shows the proposed equations can accurately predict the outcome of the Micro-Deval test. For the 18% threshold, and using the first equation above, we were able to predict the outcome at 100% accuracy. The accuracies at different threshold limits are slightly lower, but still substantially accurate.

Table 4-4 Accuracy of Micro-Deval pass/fail outcomes based on different loss limits and using different equations

	14%	16%	18%	20%	22%	24%	26%	28%	30%
3 Parameters (1)	93.10%	89.66%	100.00%	87.93%	87.93%	86.21%	94.83%	100.00%	100.00%
3 Parameters (2)	91.38%	86.21%	93.10%	91.38%	89.66%	91.38%	94.83%	100.00%	100.00%
4 Parameters	89.66%	91.38%	100.00%	93.10%	86.21%	91.38%	96.55%	100.00%	100.00%

Additional logistic regression analyses were performed to predict the outcome of the unconfined freeze/thaw tests; however, such efforts were not successful because there is little correlation between the unconfined freeze/thaw test and the other commonly used aggregate tests. This indicates that the unconfined freeze/thaw test truly measures a unique characteristic that is not represented in any other standard test or combination of tests.

4.2 Analysis of Data from Texas

A major national study on aggregate testing was performed in Texas [29]. Over 100 aggregate samples from different parts of the US were collected and tested. The tests performed were similar to those in the Phase I Wisconsin study, but the magnesium sulfate soundness was used instead of sodium sulfate soundness. Basic statistics for the Texas data are shown in Table 4-5.

Table 4-5 Basic statistics for the aggregate test results reported in the Texas study

	Micro-Deval	ABS	MSS	LAA	UFT	ACV
Mean	15.05	1.46	27.23	21.39	10.53	4.56
Median	13.70	1.00	25.00	21.00	6.05	3.50
Standard Deviation	0.787	0.116	1.084	0.602	1.265	0.332
Minimum	1.40	0.10	11.00	11.00	0.30	0.60
Maximum	48.80	5.70	66.00	48.00	70.30	22.40
Count	111	110	111	111	110	111

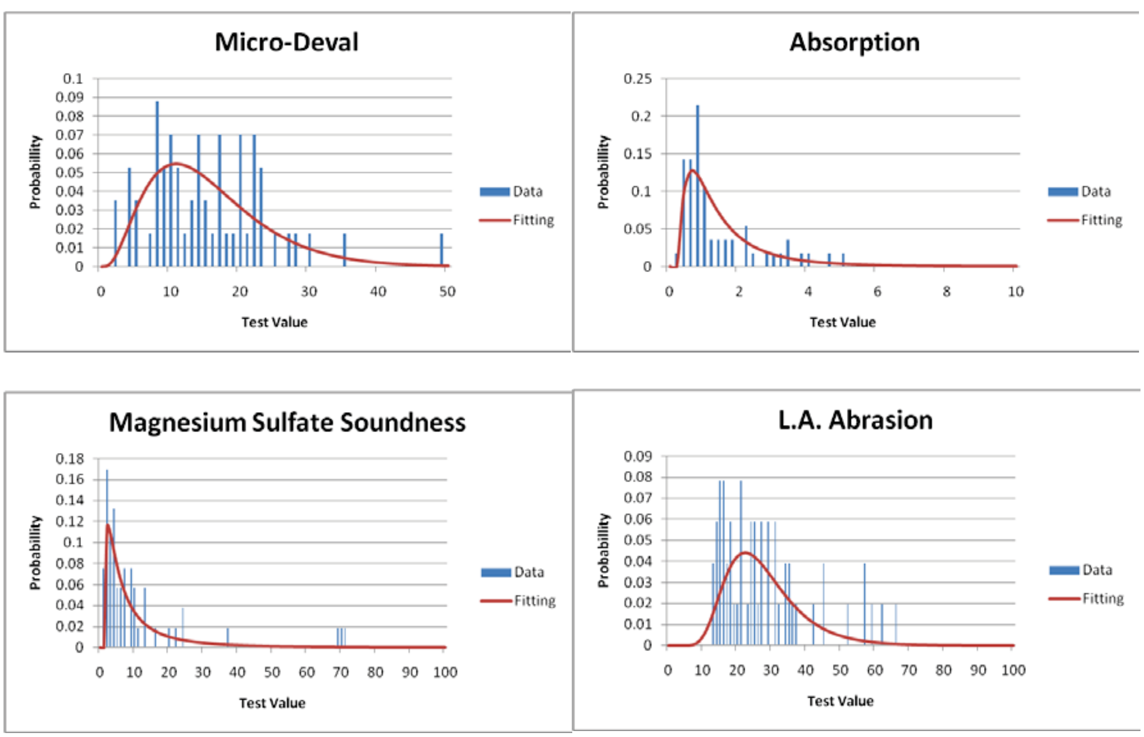


Figure 4-3 Histograms and best-fit distributions for Micro-Deval, absorption, magnesium sulfate soundness, and LA abrasion tests performed in the Texas study

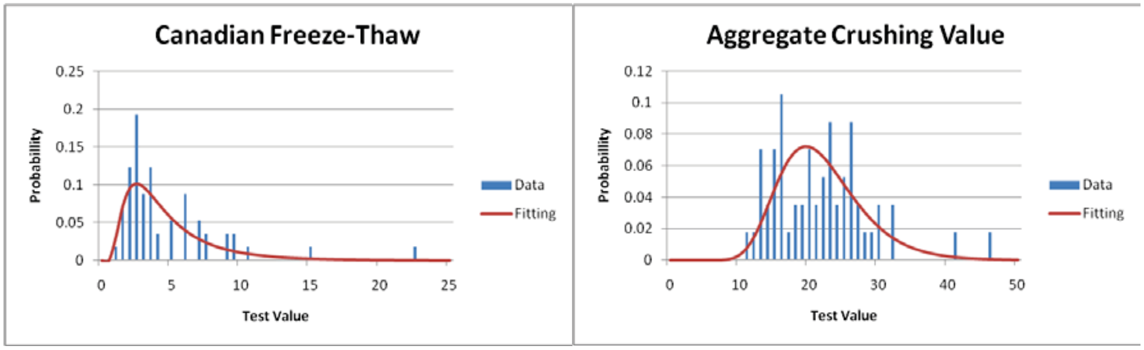


Figure 4-4 Histograms and best-fit distributions for the Canadian freeze/thaw and aggregate crushing value tests performed in the Texas study

Table 4-6 shows the best-fit distributions and respective parameters determined for each set of test results from the Texas study. Table 4-7 shows the results of a multi-parameter regression analysis performed on the Texas data. The intersection of each row and column associated with various tests shows the correlation between the two test results. For these analyses, only records with results from all tests were used. It is clear that the highest correlation exists between magnesium sulfate soundness and Micro-Deval.

Table 4-6 Best-fit statistical distributions for the Texas data

	Micro-Deval	ABS	MSS	LAA	UFT	ACV
Distribution	Gamma	LognormalE	LognormalE	LognormalE	LognormalE	LognormalE
Parameter 1	3.13251	0.05557	1.74424	3.22746	1.27562	3.02298
Parameter 2	4.80491	0.82624	1.15009	0.38614	0.69342	0.27949

Table 4-7 Correlations between results of various aggregate tests in the Texas study

Variables	Micro-Deval	ABS	MSS	LAA	CFT
Micro-Deval	1	0.60925	0.70387	0.29807	0.55002
ABS	0.60925	1	0.58180	0.21658	0.34628
MSS	0.70387	0.58180	1	0.41884	0.55555
LAA	0.29807	0.21658	0.41884	1	-0.07334
CFT	0.55002	0.34628	0.55555	-0.07334	1

Three sets of logistic regression analyses were also performed on the Wisconsin database records. The logistic regression consisted of a pass/fail outcome for the Micro-Deval test as a function of three or four parameters. Two sets of three-parameter analyses and one set of four-parameters analyses were performed as shown below:

A) Three parameters (1):

   Absorption, LA Abrasion, Magnesium Sulfate Soundness

B) Three parameters (2):

   Absorption, Magnesium Sulfate Soundness, Unconfined Freezing and Thawing

C) Four parameters:

   Absorption, LA Abrasion, Magnesium Sulfate Soundness, Unconfined Freezing and Thawing

Logistic regression analyses were performed to determine whether the pass/fail outcome of the Micro-Deval test can be determined from the other test parameters. Two three-parameter relationships (A and B) and one four-parameter relationship (C) were developed for various threshold limits for the Micro-Deval test. For example, for a commonly specified Micro-Deval limit of 18%, the following relationship was developed based on the Texas study results.

$$micro - Deval\ outcome_{18\%-A} = \frac{1}{\left(1 + e^{-(3.578 - 0.2577(ABS) - 0.1866(MSS) - 0.025(LAA))}\right)}$$

If the result of the above is greater than 0.5, the outcome is a “pass”, otherwise it is a “fail”.

$$micro - Deval\ outcome_{18\%-B} = \frac{1}{\left(1 + e^{-(2.943 - 0.257(ABS) - 0.1898(MSS) - 0.0047(CFT))}\right)}$$

$$micro - Deval\ outcome_{18\%-C} = \frac{1}{\left(1 + e^{-(3.803 - 0.283(ABS) - 0.1716(MSS) - 0.029(LAA) - 0.0466(CFT))}\right)}$$

Using the above equations, the accuracy of predictions for the outcome of the Micro-Deval test was evaluated. Table 4-8 shows that the proposed equations can predict the outcome of the Micro-Deval test to a reasonable level. For the 18% threshold, and using Eq. 4-4, we were able to predict the outcome at 85.5% accuracy. The accuracies at lower threshold limits are slightly lower.

Table 4-8 Accuracy of Micro-Deval pass/fail outcomes based on different loss limits and using different equations

	14%	16%	18%	20%	22%	24%	26%	28%	30%
3 Parameters (1)	78.18%	81.82%	85.45%	84.55%	90.00%	91.82%	90.00%	95.45%	95.45%
3 Parameters (2)	78.18%	82.73%	85.45%	85.45%	91.82%	93.64%	91.82%	95.45%	95.45%
4 Parameters	77.27%	82.73%	85.45%	86.36%	91.82%	93.64%	91.82%	95.45%	95.45%

4.3 Monte Carlo Simulations

Monte Carlo simulations were performed to predict the Micro-Deval outcome based on the proposed equations (three-parameter (1)) for the Phase I study. A threshold limit of 18% loss was selected for the simulation. The statistical distributions and copulas obtained using the Wisconsin database records were used. The Crystal Ball software program running within the Microsoft Excel® spreadsheet was used. The results (Figure 4-5) indicated that an 18% loss limit for the Micro-Deval would result is a "fail" outcome for approximately 23% of the aggregate samples from Wisconsin.

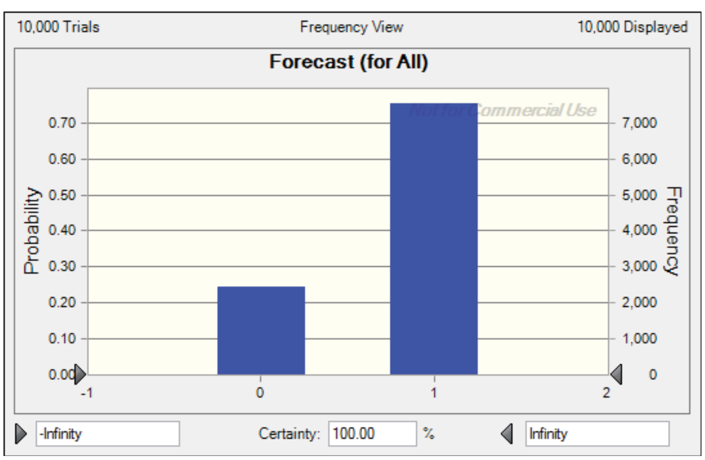


Figure 4-5 Monte Carlo simulation results for the pass ("1") and fail ("0") outcomes of the Micro-Deval test (Phase I study data)

Similar Monte Carlo simulations were performed using the Texas study distributions. The results are shown in Figure 4-6. Less than 10% of the samples represented in the Texas study would fail the Micro-Deval test.

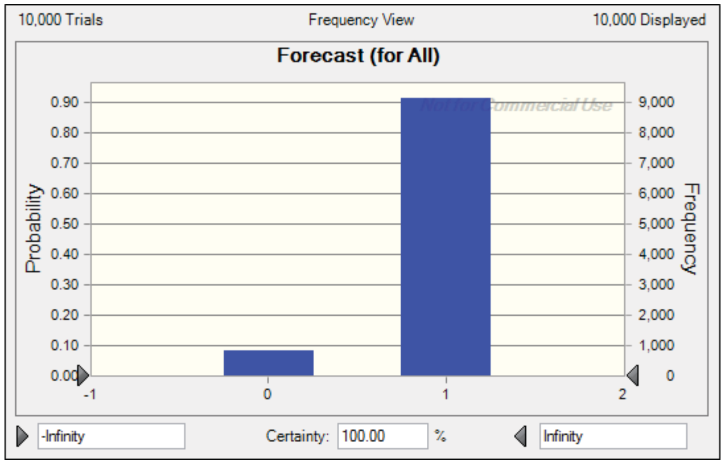


Figure 4-6 Monte Carlo simulation results for the pass ("1") and fail ("0") outcomes of the Micro-Deval test (Texas data)

In both Monte Carlo simulations, the predictive equations were based on three parameters: absorption, LA abrasion, and sulfate soundness.

Table 4-9 shows comparisons of passing percentages between Monte Carlo simulations and the results using actual database records for both Wisconsin and Texas results. This indicates the distributions and copulas used were reasonably accurate.

Table 4-9 Percentages of "pass" outcome for Wisconsin and Texas data using actual and simulated results

	WisDOT Database	Simulation Results
WHRP 02-03	72.94%	75.46%
Texas	92.75%	91.65%

4.4 Experimental Results

Twelve aggregate samples were received from WisDOT for testing, representing marginal or poor aggregates as determined by WisDOT. Table 4-10 shows descriptive characteristics of these aggregates as reported by WisDOT. Detailed test results are presented in Appendix B.

Table 4-10 Characterization of aggregate samples (by WisDOT)

Name	Predominant Rock type
Utica	Dolomite
Swiggum	Dolomite
Hauz Brothers	Limestone
Dane County	Dolomite
CC Linck	Limestone
Ramsey	Limestone
Schaefer	Dolomite
Oak Park	Dolomite
Schneider	Dolomite
Krogman	Dolomite
Ebenezer	Limestone
K Quarry	Felsic meta-volcanic (quartz-sericite schist and quatzofeldspathic gneiss)

The results of the relative density and absorption tests are shown in Table 4-11. The two relative density results represent oven-dry (OD) and saturated-surface dry (SSD) procedures.

Table 4-11 Relative density and absorption test results

Sample	Relative Density (OD)	Relative Density (SSD)	Absorption (%)
CC Linck	2.45	2.54	3.71
Hanz-Brothers	2.50	2.57	2.80
Oak Park	2.45	2.52	2.98
Ramsey	2.51	2.58	2.60
Dane	2.50	2.55	1.96
Utica	2.50	2.56	2.32
K-Quarry	2.43	2.48	1.94
Swiggian	2.37	2.46	4.07
Schaefer	2.41	2.48	3.05
Ebenezer	2.40	2.47	2.91
Krogman	2.50	2.55	2.09
Scheneider	2.47	2.53	2.46

These results are also shown in graphical form in Figures 4-7 through 4-9. The horizontal line in each figure represents the mean value for Wisconsin aggregates (from the Wisconsin database of aggregate test results). The densities for all 12 aggregate samples were less than the mean, while the absorption in all tests was higher than the Wisconsin mean. Table 4-12 shows results of the LA abrasion tests. Bar charts are given in Figure 4-10. Tables and figures for all other tests performed are also shown below.

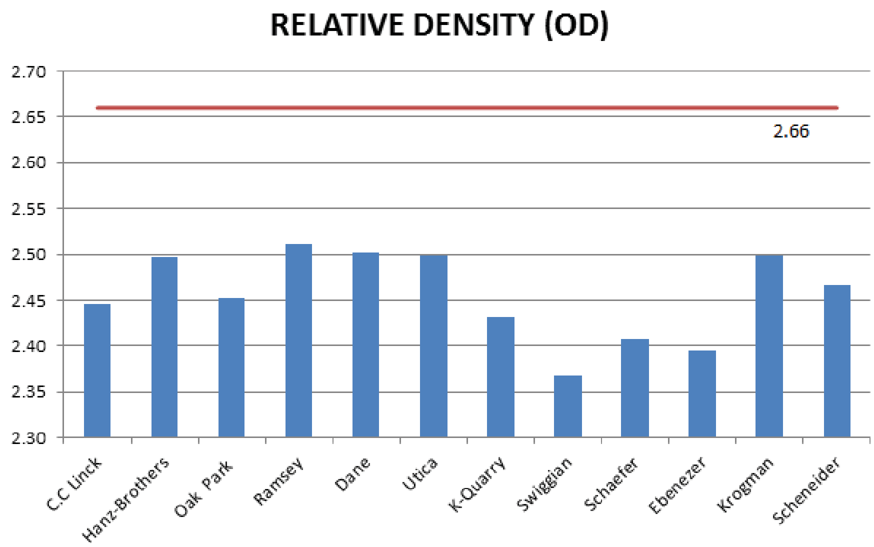


Figure 4-7 Bar charts of results of aggregate test – Relative density (OD)

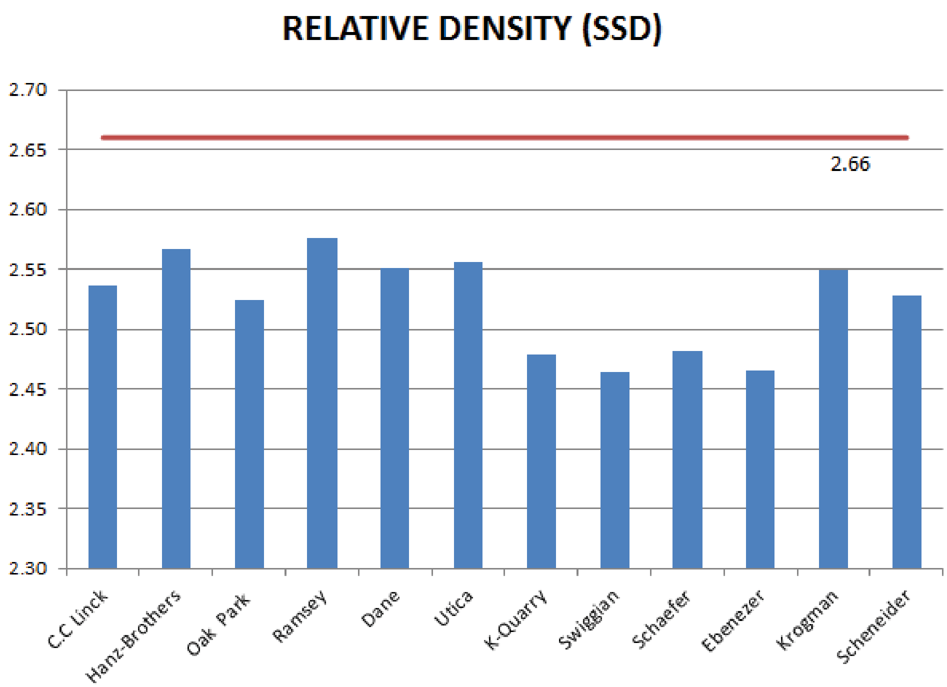


Figure 4-8 Bar charts of results of aggregate test – Relative density (SSD)

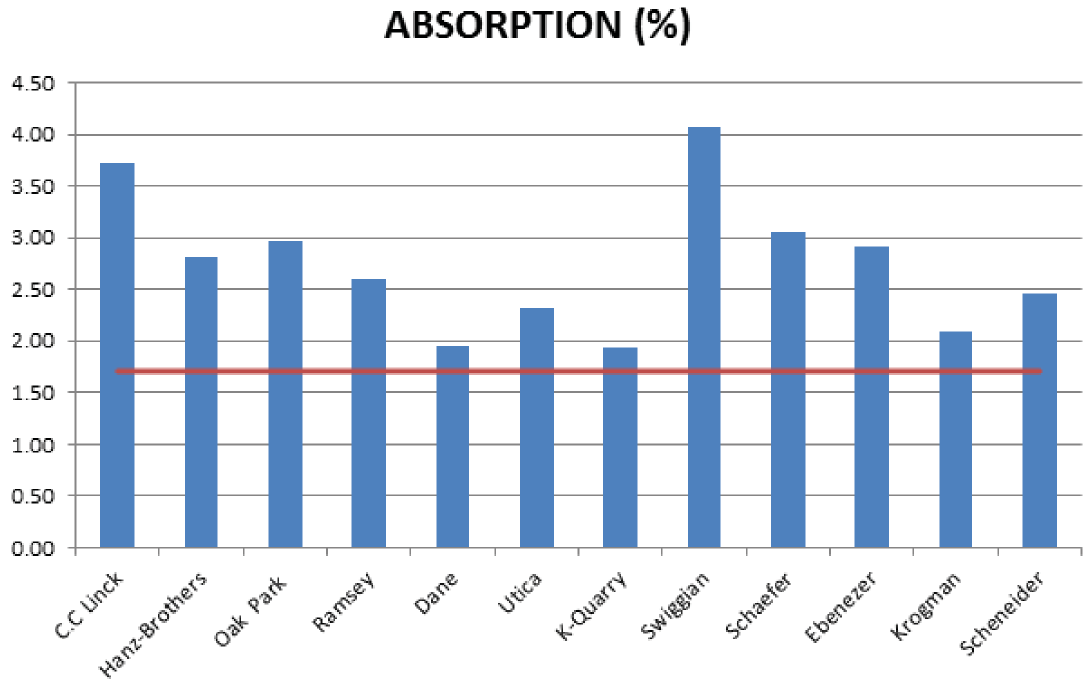


Figure 4-9 Bar charts of results of aggregate test – Absorption (%)

Table 4-12 LA abrasion test results

Sample	LA Abrasion % loss	LA Abrasion WI Mean
C.C Linck	36.6	29.3
Hanz-Brothers	30.2	29.3
Oak Park	31.3	29.3
Ramsey	35.7	29.3
Dane	38.6	29.3
Utica	36.3	29.3
K-Quarry	21.5	29.3
Swiggian	41.1	29.3
Scheafer	40.5	29.3
Ebenezer	33.6	29.3
Krogman	35.3	29.3
Schneider	39.6	29.3

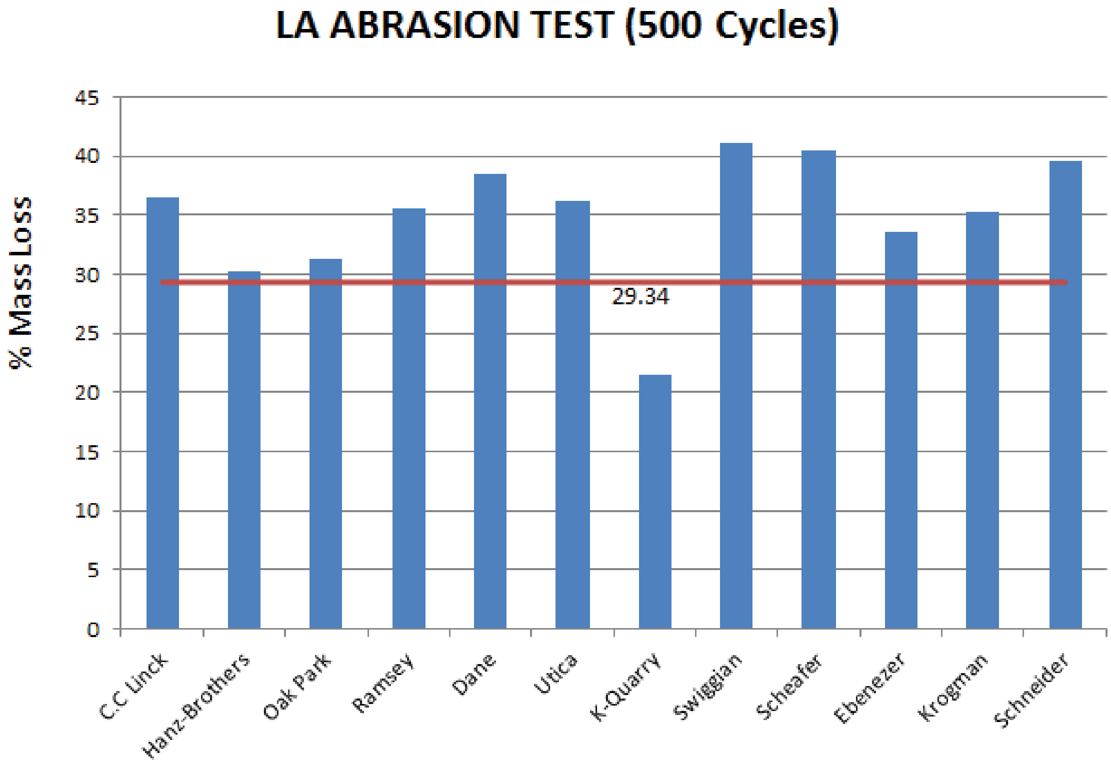


Figure 4-10 Bar charts of results of aggregate test – LA abrasion – 500 cycles (% loss)

Table 4-13 Unconfined freeze/thaw test results

Sample	Unconfined Freeze/thaw % loss	Unconfined Freeze/thaw WI Mean
C.C Linck	22.9	1.57
Hanz-Brothers	31.8	1.57
Oak Park	15.4	1.57
Ramsey	7.6	1.57
Dane	0.6	1.57
Utica	14.0	1.57
K-Quarry	11.9	1.57
Swiggian	0.5	1.57
Scheafer	5.7	1.57
Ebenezer	27.3	1.57
Krogman	4.6	1.57
Schneider	3.2	1.57

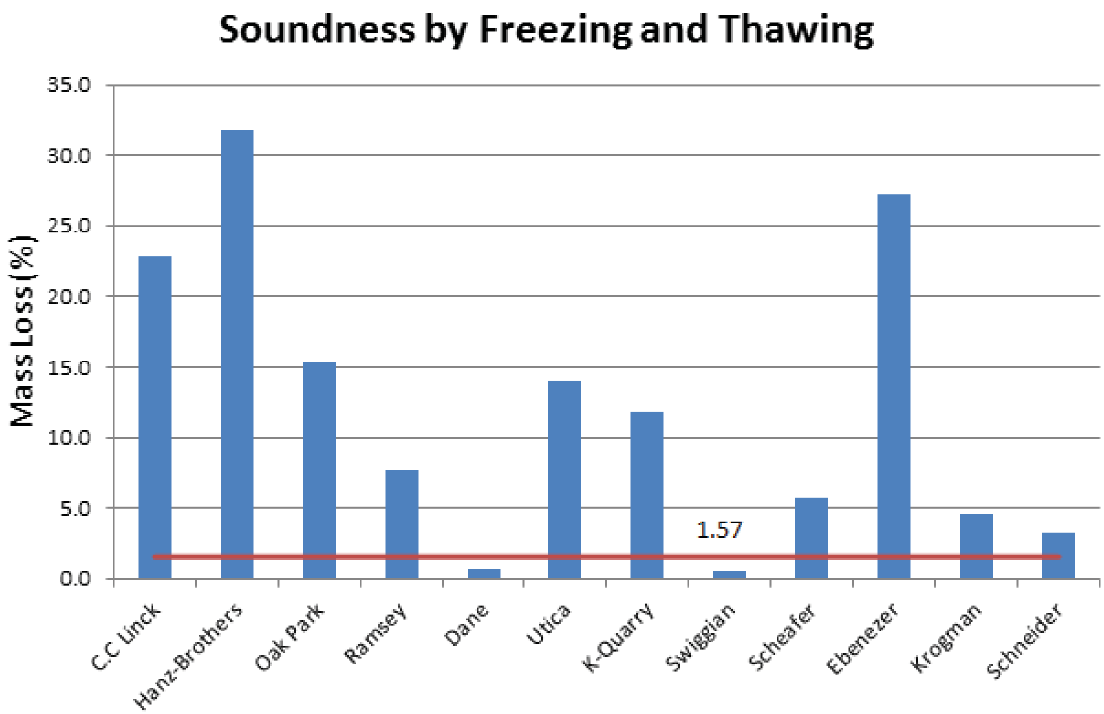


Figure 4-11 Bar charts of results of aggregate test – LA abrasion – 500 cycles (% loss)

Table 4-14 Sodium sulfate soundness test results

Sample	**Sodium Sulfate Soundness % loss**	**Sodium Sulfate Soundness WI Mean**
CC Linck	21.82	2.36
Hanz-Brothers	12.75	2.36
Oak Park	3.97	2.36
Ramsey	2.61	2.36
Dane	1.17	2.36
Utica	5.97	2.36
K-Quarry	1.85	2.36
Swiggian	0.23	2.36
Scheafer	0.17	2.36
Ebenezer	2.91	2.36
Krogman	0.21	2.36
Schneider	0.78	2.36

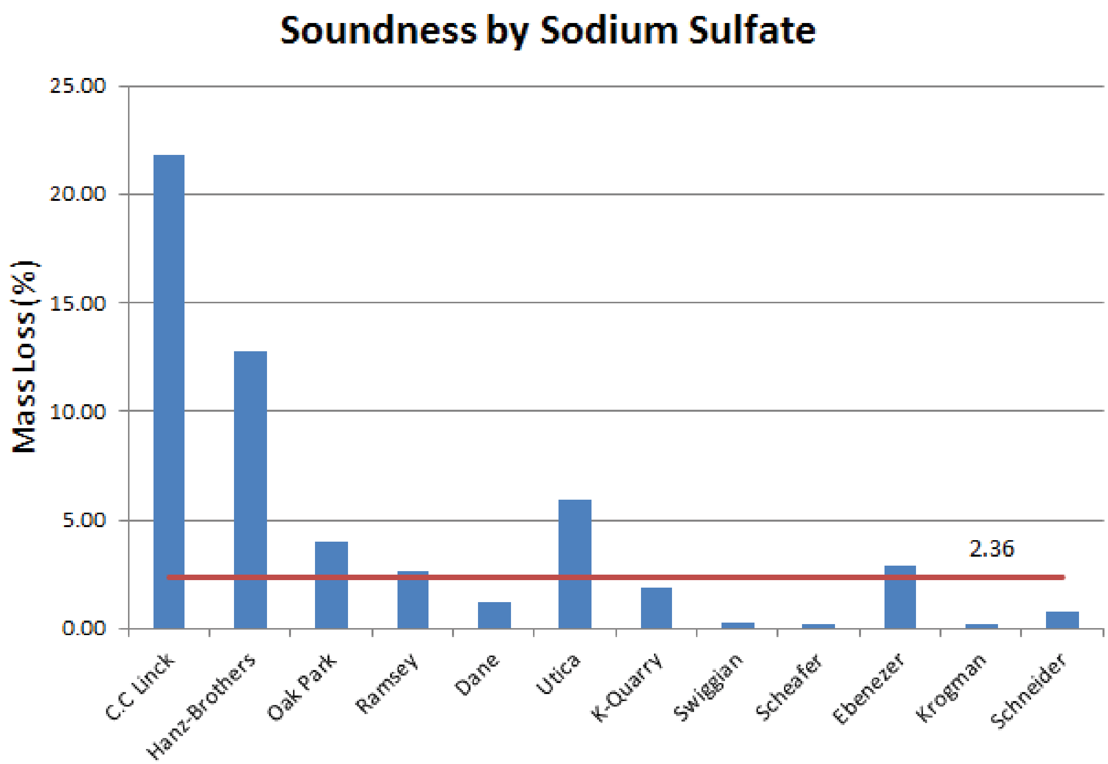


Figure 4-12 Bar charts of results of aggregate test – Sodium sulfate soundness (% loss)

Table 4-15 Micro-Deval test results

Sample	Micro-Deval % loss	Micro-Deval WI Mean
C.C Linck	38.70	15.05
Hanz-Brothers	31.19	15.05
Oak Park	17.78	15.05
Ramsey	17.26	15.05
Dane	20.15	15.05
Utica	17.85	15.05
K-Quarry	30.84	15.05
Swiggian	20.47	15.05
Scheafer	22.33	15.05
Ebenezer	30.17	15.05
Krogman	17.62	15.05
Schneider	18.97	15.05

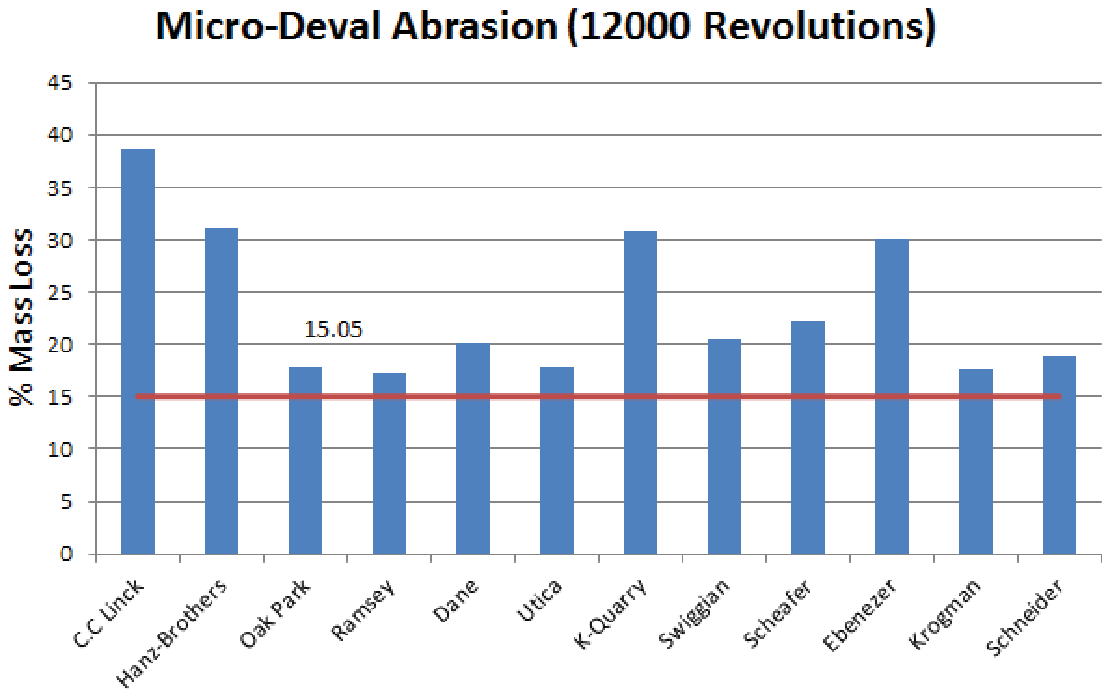


Figure 4-13 Bar charts of results of aggregate test – Micro-Deval (% loss)

CHAPTER 5

X-RAY COMPUTED TOMOGRAPHY ANALYSIS

The X-ray Computed Tomography (CT), a novel method that has recently emerged as a non-destructive technique for material characterization, was used to investigate the pore structure of selected aggregates. In this method, an object is scanned by directing an incident X-ray beam towards the object. The X-ray that passes through the object is collected with an array of detectors. The object is rotated such that the X-ray beam probes from several angles to collect attenuation data and produce the equivalent of a cross-sectional “slice” through the region of interest. This method produces three-dimensional (3D) images (rendering) of the object that can be analyzed in various ways based on the purpose of the scan.

Virgin aggregate and treated aggregate (sodium sulfate soundness and unconfined freeze/thaw tests) specimens were subjected to X-ray CT to obtain high-resolution 3D images. The aggregates scanned in this study are: CC Link, Dane, HanzBr, Oak Park, Ramsey, and Utica. The CT scans were carried out using a sector 13-BMD synchrotron microtomography beamline at the Advanced Photon Source (APS) of the Argonne National Laboratory, Illinois. The Advanced Photon Source is one of the world’s most brilliant sources for synchrotron light. Figure 5.1 depicts an aerial photograph of APS.

5.1 Computed Tomography Procedure

Computed tomography scans were conducted at beamline 13-BM-D of APS during two separate visits. In order to acquire high-resolution images for this research, the aggregate samples must be small enough to fit in the beam (<5 mm wide). The first step is to place a sample on the translation/rotation stage, then set up the X-ray intensity and resolution. Figure 5.2 shows the placement of the aggregate sample on the stage as vertically as possible to help prevent any imaging artifacts. The experiment hutch was then searched and the door was closed and magnetically locked. The lights inside the hutch were turned off and the slit shutters were opened to allow X-rays to travel along the designated path through the sample and scintillator and into the camera.

Figure 5-1 The Advanced Photon Source at Argonne National Laboratory, Illinois

The setup process involved zooming and focusing the camera to capture the entire sample clearly with some air on each side, and selecting the optimal energy to capture all aspects of the sample. The X-ray source is filtered to a single energy optimal for the aggregate by rotating the crystal monochromaters, which were kept parallel. Unwanted X-ray energies are reflected by the crystalline structure in the monochromaters according to Bragg's Law, and based on the angle of rotation, allow only a very narrow band of energy (very close to one single energy) through them. The exposure time for a sample was balanced with the energy to achieve a clear image.

Figure 5-2 CT scanning of the investigated aggregates at APS

The scans acquired were unbinned with a field of view of 4.96 mm wide × 3.71 mm high with an exposure time of 1.93 seconds and energy of 28 keV per scan, which resulted in a resolution of 3.56 µm per voxel. The scans of the second occasion were also unbinned with a field of view of 6.44 mm wide × 4.82 mm high, exposure time of one second, 28 keV energy and resulting resolution of 4.63 µm per voxel.

For each sample, scans were acquired at every 0.2 degrees over 180 degrees rotation, resulting in 900 scans. The sample was constantly rotating and scans were taken on the fly instead of stopping the sample for every scan, which decreased the scanning time. For every 100 angles, 10 dark current and 10 white field images were taken to calibrate the images and help reduce image artifacts.

5.2 Post-Processing

In order to characterize pore space and pore space distribution and connectivity in the investigated aggregate particles using X-ray CT, post-processing of the acquired images was conducted. Analysis of pore space growth due to cycles of sodium sulfate and freeze/thaw soundness tests was also of interest. From 3D CT constructed images, the pore structure can be visualized in 2D by the slices and can also be visualized and accurately quantified in 3D. Individual pores can be quantified in terms of their size, shape, and connectivity; therefore, pores connected to the surface of the aggregate and pores isolated within the aggregate particle can be differentiated. Before any quantification can occur, post-processing of the images must be completed.

The workstation used for post processing is a Dell Precision T3500 with a Quad Core Intel® Xeon® Processor E5630 with 24 GB of memory and a 2GB NVIDIA® Quadro® 4000 graphics card. The analysis program used is Avizo® Fire version 6.3.1 from Visualization Sciences Group. Avizo Fire has a broad range of software tools for obtaining and visualizing advanced qualitative and quantitative information on material structure images. A display of the Avizo Fire interface is shown in Figure 5.3

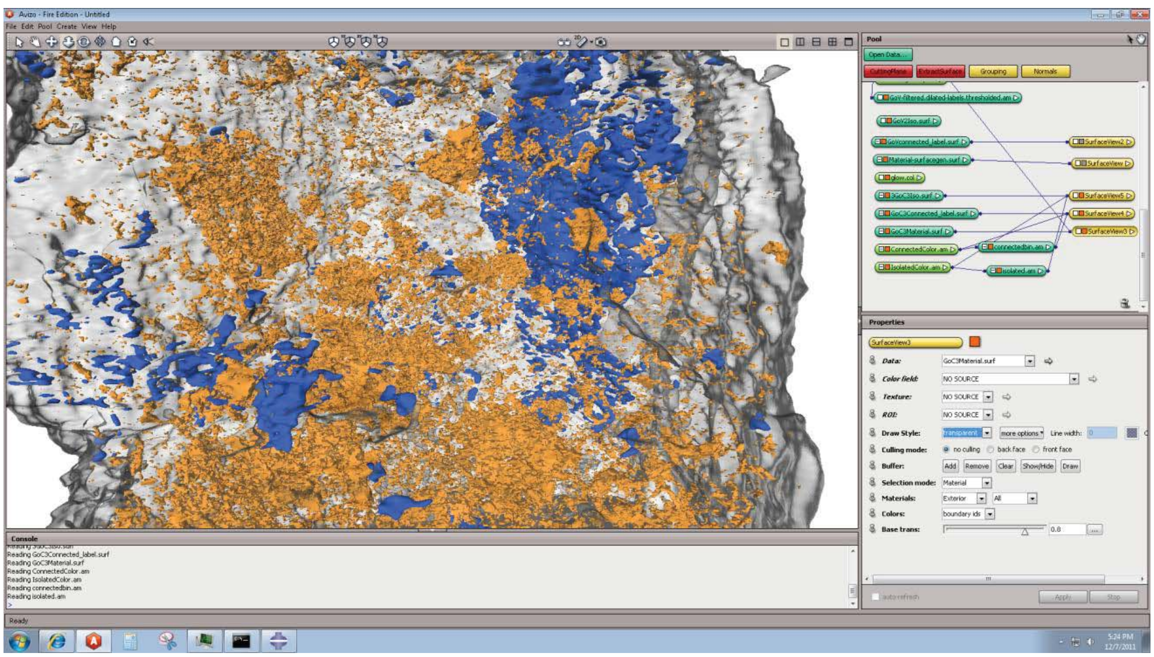
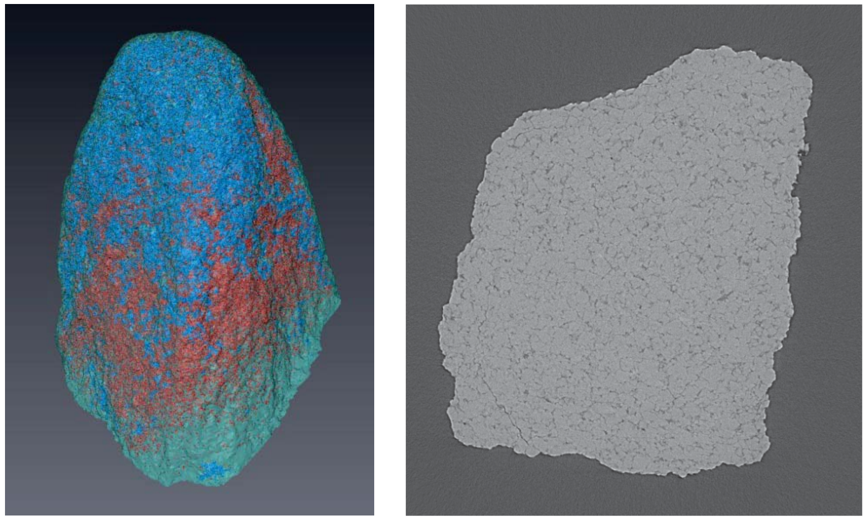


Figure 5-3 Avizo Fire software interface used for post-processing data

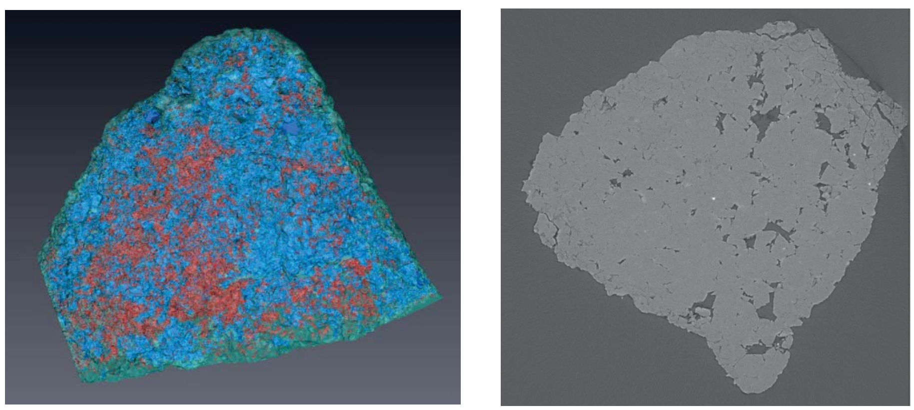
The main post processing steps for quantifying pore space within the aggregate include segmenting the image through thresholding, isolating the image from the background, isolating each pore, and quantifying the characteristics of each pore. Details of post-processing pertaining to pore space characterization in aggregates are presented by Titi et al. (2011). At the end of post-processing, the geometry (pore and solid) can be viewed in 3D, which provides useful insight on the internal structure of the aggregate particle. The 3D visualization provides useful information on pore connectivity, tortuosity, distribution, and size, which can be used to characterize aggregate behavior with respect to durability and ability to resist external forces from environmental impact and loading.

5.3 Analyses of Results

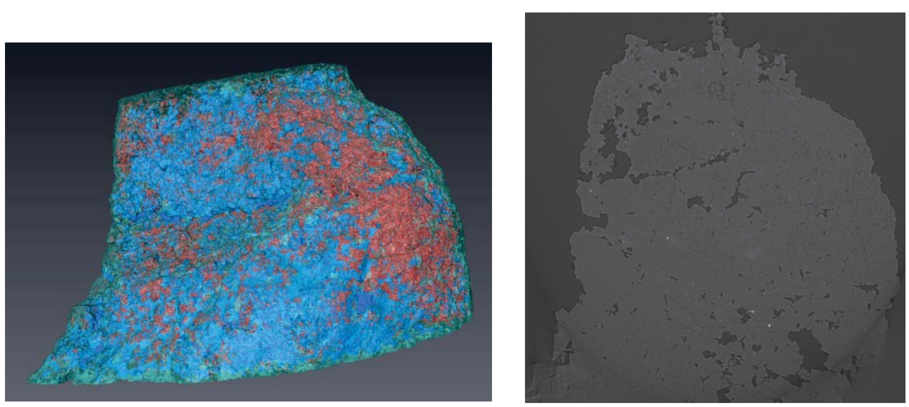
Figure 5.4 shows CT constructed 3D images and slices for Utica aggregate: virgin specimen and specimens subjected to unconfined freeze/thaw and sodium sulfate soundness tests. Figure 5.4a shows the 3D view of the pore space within a Utica virgin aggregate. The 3D image shows two types of pore space: isolated pores within aggregate solid (blue color) that are not connected to the external surface, and pores that are connected to other pores and to the external surface of the aggregate particle (red color). The virgin Utica aggregate possesses a pore structure that is uniformly distributed within the aggregate mass, and the sizes of the pores are relatively small. Figures 5.5 to 5.9 show CT constructed 3D images and slices for the rest of the investigated aggregates under virgin, freeze/thaw and sodium sulfate soundness tests conditions. Inspection of the 3D image and cross-sectional slices shows the presence of increased pore space and developed cracks on the aggregates subjected to freeze/thaw and sodium sulfate soundness tests.



a) Virgin

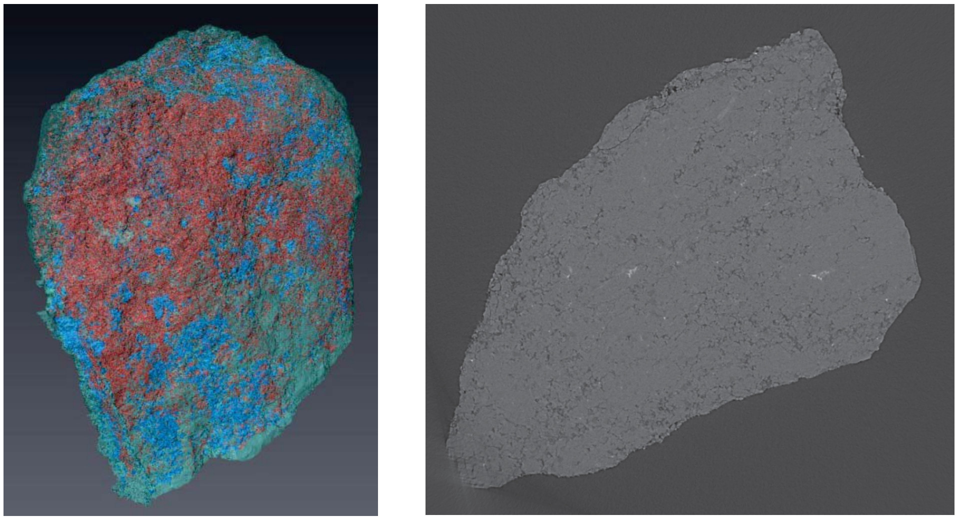


b) Freeze/Thaw

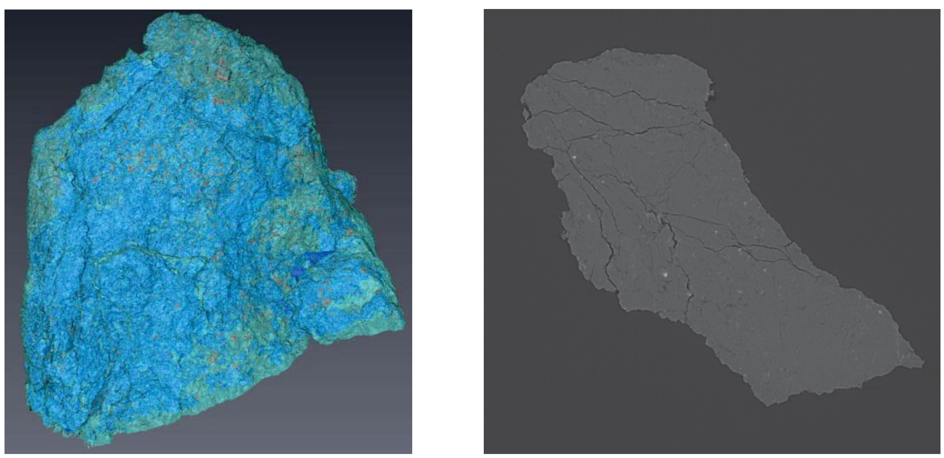


c) Sodium Sulfate Soundness

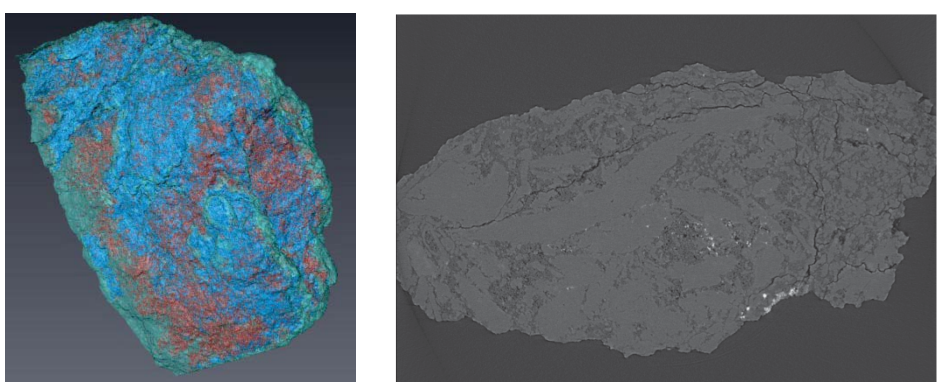
Figure 5-4 CT constructed 3D image of the Utica aggregate



a) Virgin

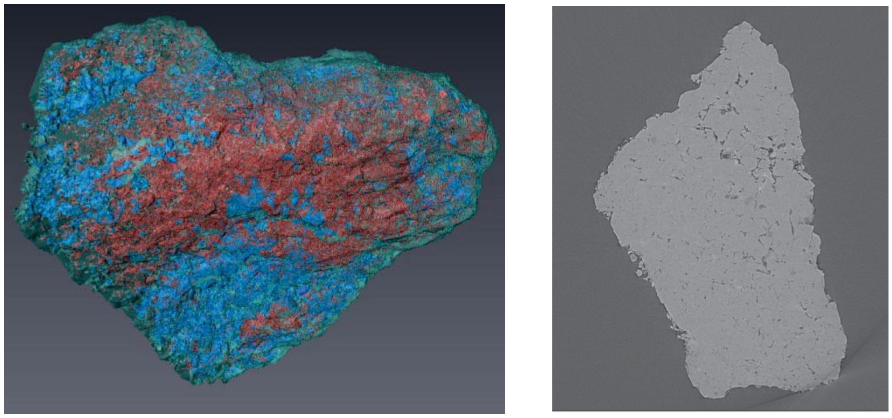


b) Freeze/Thaw

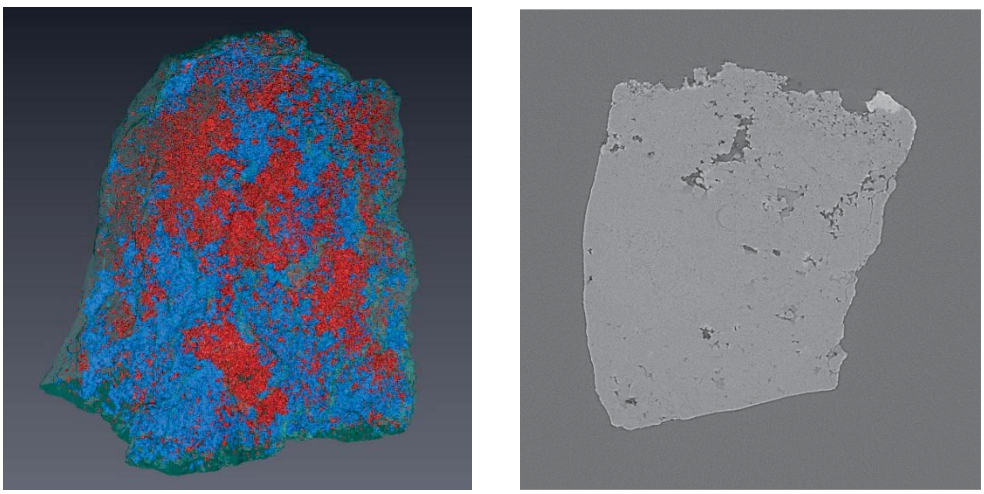


c) Soundness

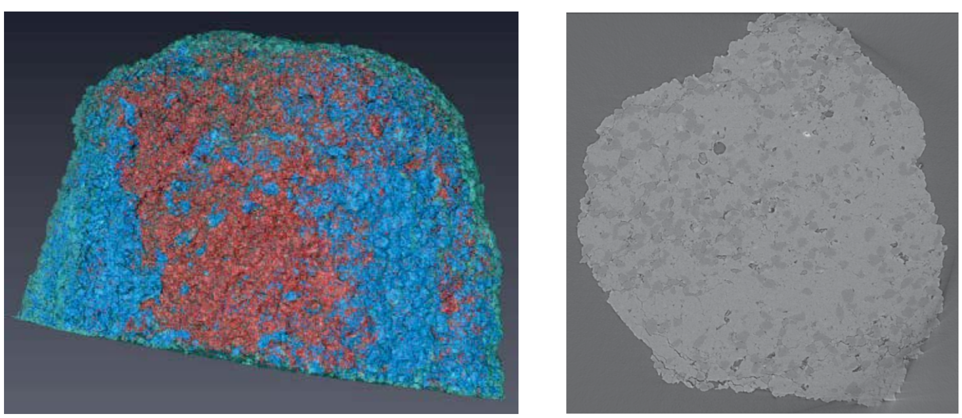
Figure 5-5 CT constructed 3D image of the CC Link aggregate



a) Virgin



b) Freeze/Thaw



c) Soundness

Figure 5-6 CT constructed 3D image of Dane aggregate

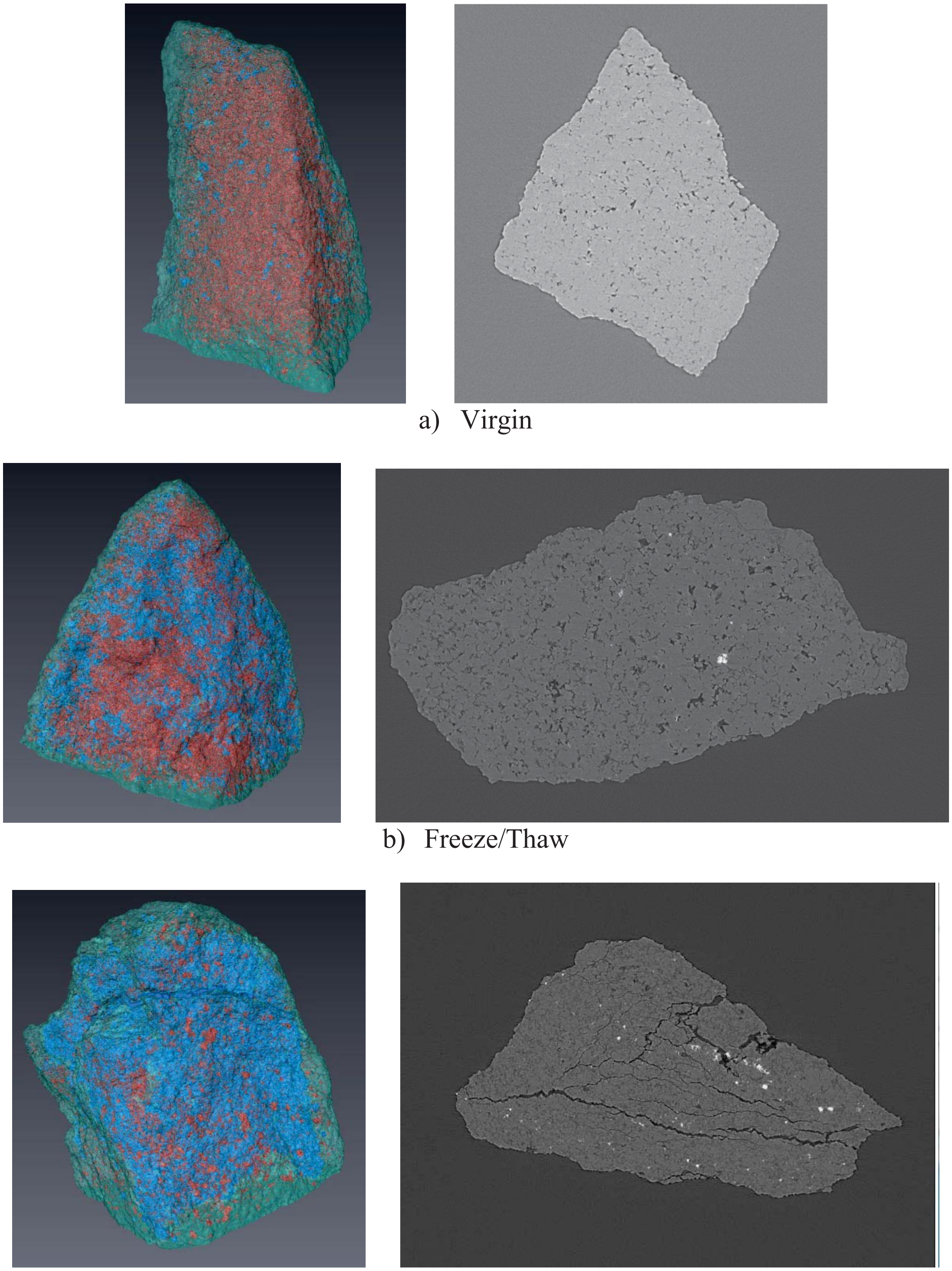
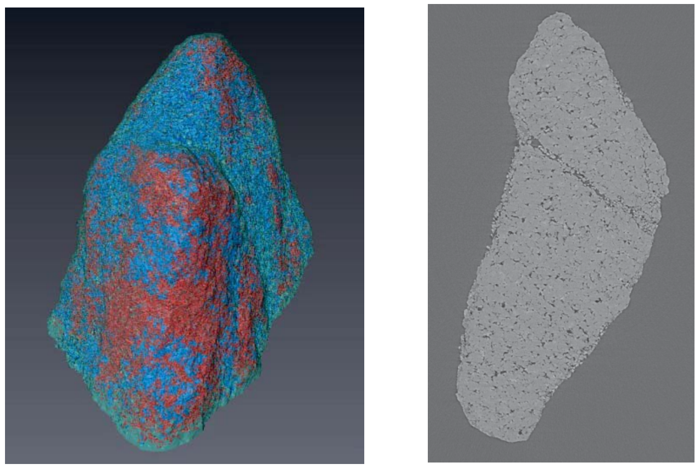
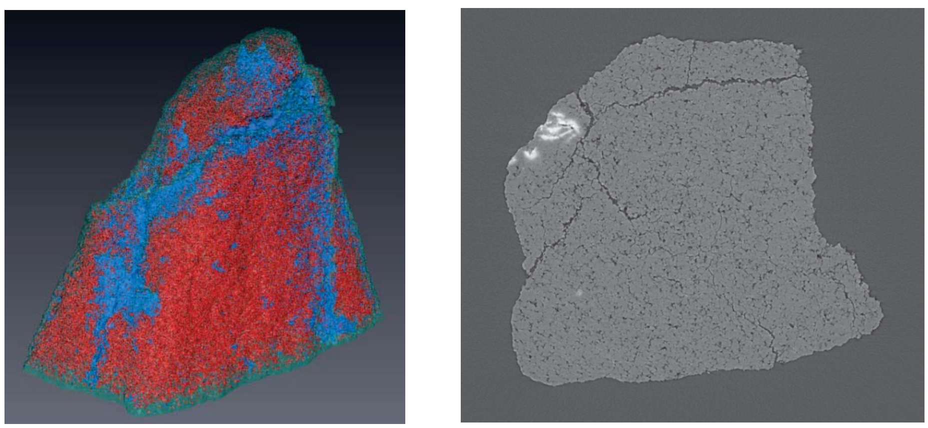


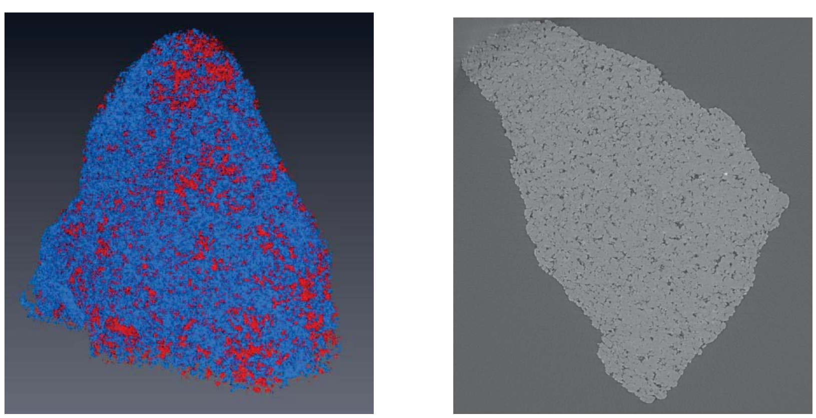
Figure 5-7 CT constructed 3D image of HanzBr aggregate



a) Virgin

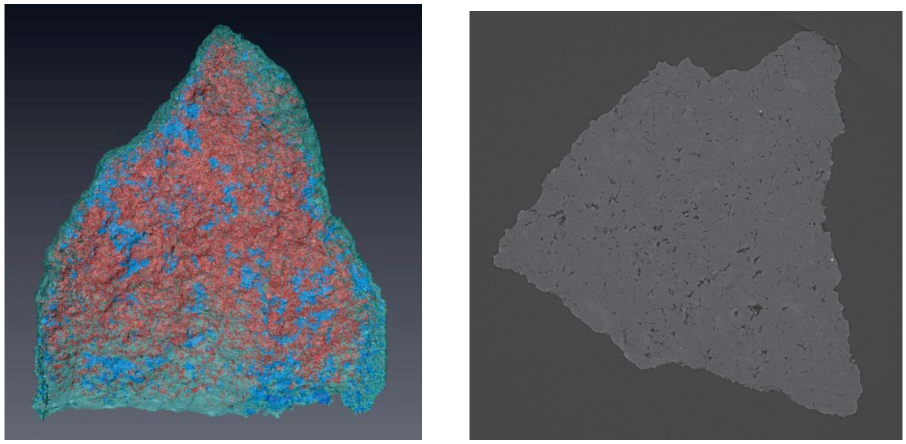


b) Freeze/Thaw

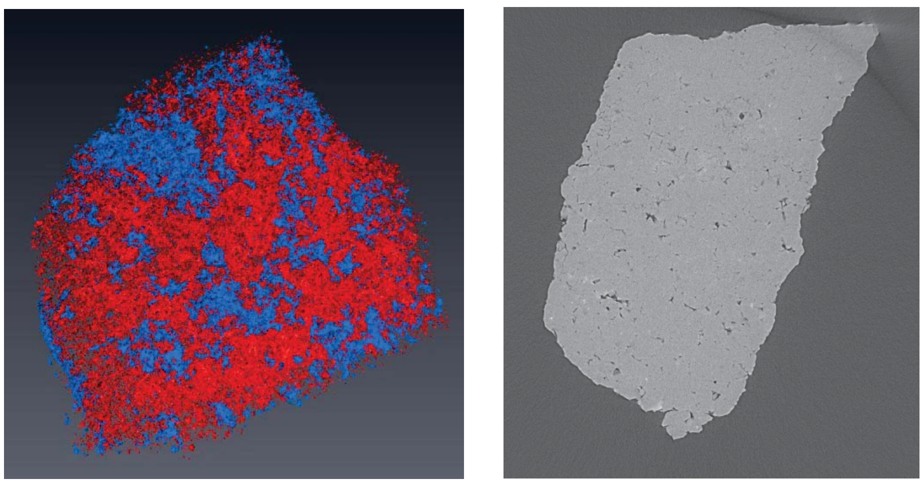


c) Soundness

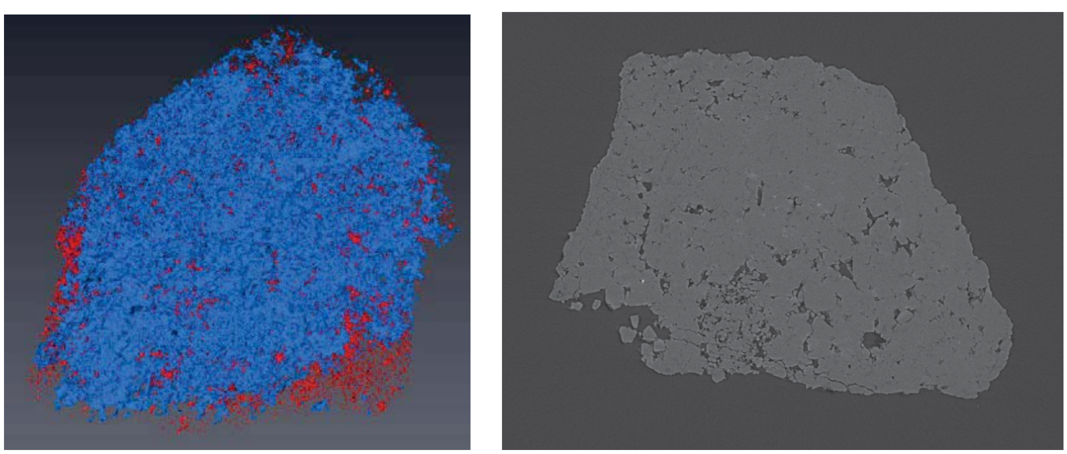
Figure 5-8 CT constructed 3D image of Oak Park aggregate



a) Virgin



b) Freeze/Thaw



c) Soundness

Figure 5-9 CT constructed 3D image of Ramsey aggregate

Figure 5.10 depicts a 3D image of HanzBr aggregate with significant cracking as a result of the sodium sulfate soundness test.

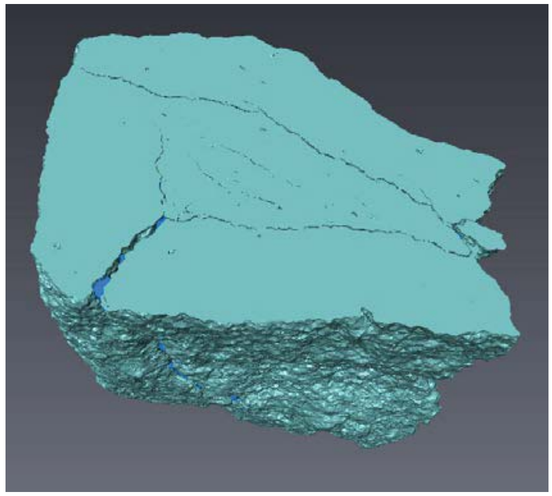


Figure 5-10 3D image of HanzBr aggregate with significant cracking due to sodium sulfate soundness test

The characteristics of pore space for the investigated aggregate samples were measured. Each aggregate sample contains thousands of individual pores; therefore, pore space analysis was conducted using spreadsheets. The total volume of the solid material, volume of pores connected to the aggregate surface, and volume of isolated pores were measured and used to calculate the porosity of the investigated aggregate samples. The total porosity of the aggregate and the porosity of the aggregate in terms of the pores connected to the surface and pore completely isolated were calculated. The total porosity is calculated as:

$$n_T = \frac{V_V}{V_T} = \frac{V_V}{V_S + V_V} = \frac{V_{Vc} + V_{Vi}}{V_S + V_{Vc} + V_{Vi}} \quad (5.1)$$

Where n_T= the total porosity, V_V is the volume of all voids, V_T is the total volume of the sample, including solid material and voids, V_S is the volume of the solid material, V_{Vc} is the volume of the pores connected to the surface of the aggregate sample and V_{Vi} is the volume of the pores isolated within aggregate solid. The porosity of an aggregate particle considering pores connected to the surface (n_c) is given by:

$$n_c = \frac{V_{Vc}}{V_S + V_{Vc} + V_{Vi}} \tag{5.2}$$

The porosity of the aggregate based on isolated pores (n_i) is the difference between the total and connected porosities:

$$n_i = n_T - n_c \tag{5.3}$$

Equations 5.1 to 5.3 were used to calculate the porosities of the investigated virgin and treated aggregate particles. Table 5.1 summarizes the results of aggregate solid and pore space volume measurements from 3D CT images and the corresponding porosities for all investigated aggregates. For CC link virgin aggregate, the total porosity of the virgin sample is 1.455%, and the porosity considering only pores connected to the surface of the aggregate is 0. 408%, as depicted in Table 5.1. The porosity of the sample that was subjected to freeze/thaw test is 5.376%, while the porosity of the samples subjected to the sodium sulfate test is 3.262%, demonstrating a significant increase in the pore space of treated aggregate compared with the aggregate virgin sample of the same aggregate type.

Table 5-1 Porosity of the investigated aggregates

No.	Aggregate	Treatment	Isolated Porosity	Connected Porosity	Total Porosity
1	CCLink	Freeze/thaw	0.00973	0.04403	0.05376
		Soundness	0.01685	0.01576	0.03262
		Virgin	0.01047	0.00408	0.01455
2	Dane	Freeze/thaw	0.01623	0.01465	0.03088
		Soundness	0.02160	0.01838	0.03998
		Virgin	0.01239	0.01183	0.02422
3	HanzBr	Freeze/thaw	0.02120	0.04471	0.06591
		Soundness	0.00685	0.03096	0.03781
		Virgin	0.02184	0.00070	0.02254
4	Oak Park	Freeze/thaw	0.04149	0.02053	0.06202
		Soundness	0.02123	0.05330	0.07454
		Virgin	0.03562	0.03767	0.07329
5	Ramsey	Freeze/thaw	0.01677	0.00793	0.02471
		Soundness	0.00685	0.06567	0.07252
		Virgin	0.01715	0.00396	0.02110
6	Utica	Freeze/thaw	0.00994	0.07683	0.08677
		Soundness	0.02640	0.03273	0.05913
		Virgin	0.02650	0.01130	0.03780

Figure 5.11 shows the total porosity, porosity of aggregate particle with respect to pores connected to the surface, and porosity of aggregate with respect to pores isolated within the particle solid of the investigated virgin aggregate samples. Inspection of the figure indicates, in general, the isolated pore space is larger, for most samples, than the connected pore space. The influence of the freeze/thaw and sodium sulfate tests on the pore space of the investigated aggregates is presented in Figure 5.12.

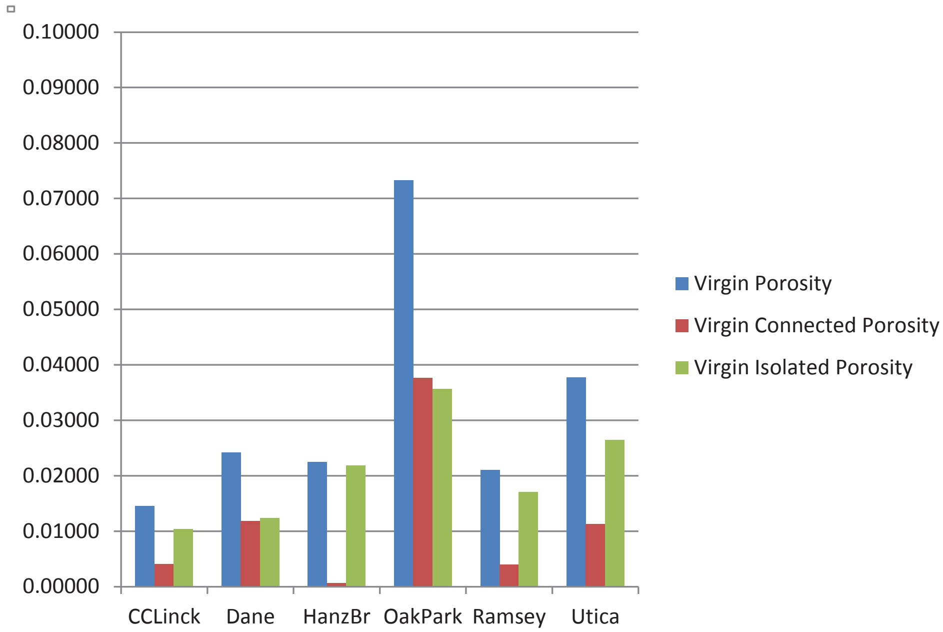


Figure 5-11 Porosity of the investigated virgin aggregate samples

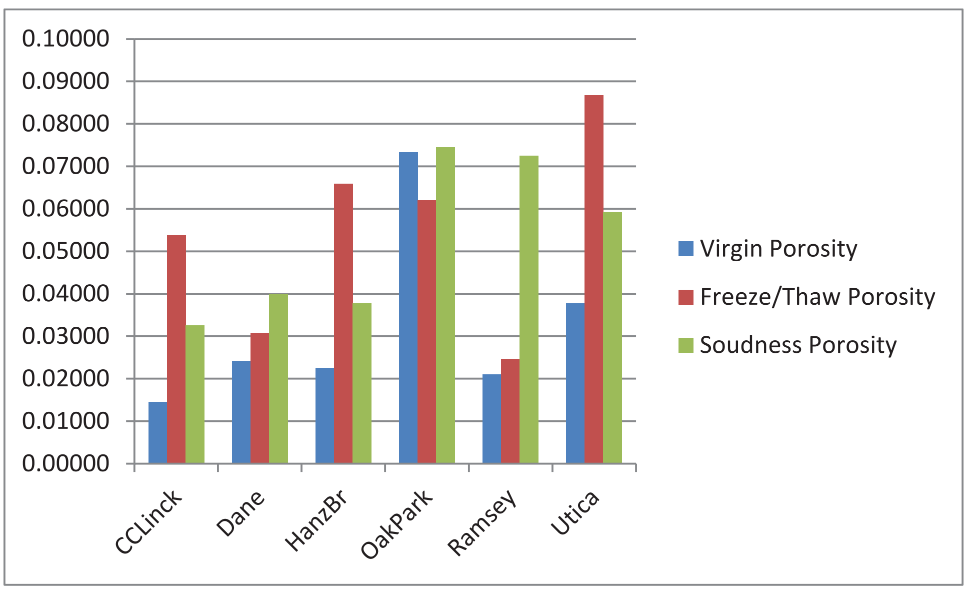


Figure 5-12 Influence of freeze/thaw and soundness tests on porosity of the investigated aggregate samples

Figure 5.12 demonstrates the increase of pore space as the aggregate samples are subjected to harsh environmental conditions through the unconfined freeze/thaw and sodium sulfate tests. Pores that are connected to the surface of the aggregate are also highly connected to each other, indicating that thin solid material barriers between pores may be degrading as the aggregate is subjected to freezing/thawing and wetting/drying during the freeze/thaw and sodium sulfate soundness test cycles. The connected (permeable) pores allow the penetration of the water and sodium sulfate during the tests. Internal expansion force/pressure develops due to water freezing and re-hydration of the sodium sulfate upon re-wetting (after drying cycle) causing weathering/disintegration of solid material. It can be stated that the increase in pore space due to freeze/thaw and soundness tests primarily occurred due to the increase in connected pore space, while isolated pore space did not significantly increase, as demonstrated in Figures 5.13 and 5.14.

The increase in connected pore space due to freeze/thaw and sodium sulfate tests is presented in Figure 5.15. The ratio of connected pore space of aggregate particles subjected to the freeze/thaw test significantly increased with a range from 45 to 6,391%, while the increase varies from 141 to 4,426% for aggregates subjected to the sodium sulfate soundness test. Such increase with different amounts affects the durability of the aggregate at different levels, leading to variable field performance. It should be noted that CT pore space analysis of the investigated aggregates did not show correlation or a behavior trend between samples subjected to the unconfined freeze/thaw and sodium sulfate soundness test. Aggregates from CC Link, HanzBr, and Utica showed a significant increase in the freeze/thaw test, while aggregates from Dane, Oak Park, and Ramsey exhibited a significant increase after the sodium sulfate soundness test.

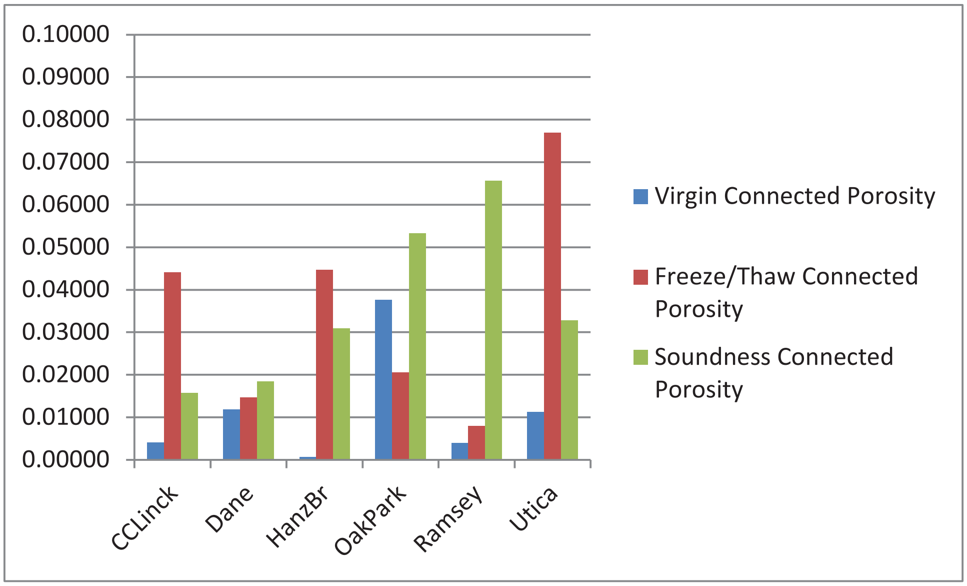


Figure 5-13 Increase in connected pore porosity due to freeze/thaw and soundness tests of the investigated aggregate samples

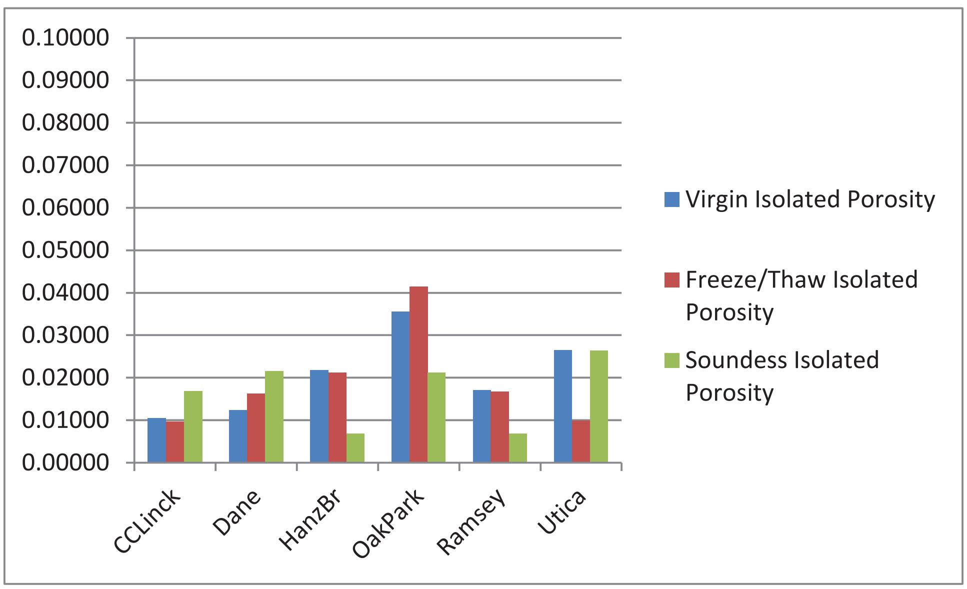


Figure 5-14 Isolated pore porosity remained relatively unchanged due to freeze/thaw and soundness tests of the investigated aggregate samples

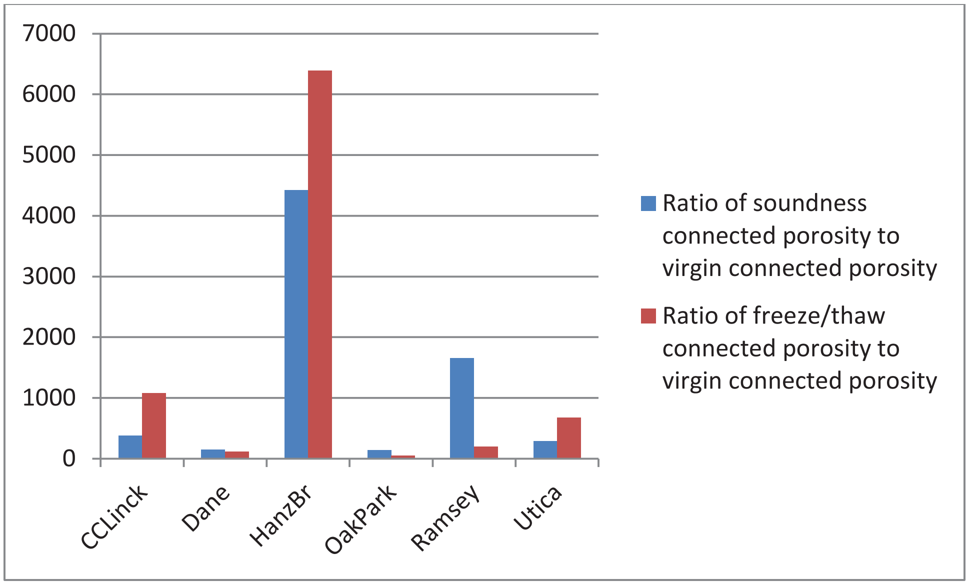


Figure 5-15 Increase in connected pore space due to freeze thaw and sodium sulfate soundness tests

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

The historical results of aggregate tests in Wisconsin were evaluated in this study, and relationships between Micro-Deval test outcomes and other established test methods were developed. Statistical distributions for various aggregate test results were determined. Three sets of distributions were determined using data from: 1) pits and quarries combined; 2) pits; and 3) quarries. The results of a Texas study performed by Fowler et al. [29] (on 110 aggregate samples from various parts of the United States) were analyzed to developed statistical relationships.

Statistical copulas between various test distributions were developed to facilitate Monte Carlo simulations. Monte Carlo statistical simulations were performed to predict the pass/fail outcomes of Micro-Deval tests on Wisconsin aggregates and national aggregate tests performed in Texas. Multi-parameter regression analyses (including logistic regressions) were performed and correlations between various test results were established for all three datasets. Three- and four-parameter logistic regression relationships were developed to predict the pass/fail outcomes of Micro-Deval tests for the three datasets. For Wisconsin data (Phase I study), the Micro-Deval outcomes with an 18% loss limit were predicted 100% correctly for all aggregate tests performed. The prediction accuracy for a 16% Micro-Deval loss limit was 90%. For the limited national test data (Texas study), the accuracy for the 18% and 16% Micro-Deval loss limits were 85% and 82%, respectively. This lower accuracy is expected due to the wide variety of aggregates tested in the Texas study.

Based on the statistical analysis of the Wisconsin aggregate test database, the 75 percentile limits for various aggregate tests are: LA abrasion (35.5%), sodium sulfate soundness

(5.65%), unconfined freeze/thaw test (6.0%), absorption (fine aggregates) (0.95%), and absorption of coarse aggregates (2.27%). The research team recommends checking all threshold limit requirements for percentile level to ascertain the impact of those limits.

The following conclusions can be made based on this study:

- The outcome of the Micro-Deval test on Wisconsin aggregates could be predicted well using the proposed three- or four-parameter logistic regression equations.
- The unconfined freeze/thaw test does not correlate with the other tests, either individually in a multi-parameters numerical regression or in multi-parameter logistic regressions; thus, the unconfined freeze/thaw test is truly measuring a characteristic that is not measured in other tests, either individually or collectively. The X-ray tomography scans further verified this observation. The unconfined freeze/thaw should be a standalone requirement in any aggregate acceptance test protocol, because its results cannot be deduced from any other test or combination of tests.
- The 75 percentile point in the historical Wisconsin database for each type of aggregate test is a reasonable basis for the threshold limit for that test. Therefore, the following threshold limits may be considered:
    - LA abrasion: 35%
    - Sodium sulfate soundness: 6%
    - Unconfined freeze/thaw test: 6%
    - Absorption (fine): 1%
    - Absorption (coarse): 2.3%

Twelve aggregate samples were received from WisDOT for testing; the samples represented marginal or poor aggregates as determined by WisDOT.

Although not included in the original project scope, the research team performed high-resolution X-ray computed tomography (CT) scans on six aggregate sources that were subjected to freeze/thaw testing and sodium sulfate soundness testing. The scans were conducted at the Argonne National Laboratory's Advanced Photon Source (APS) facility near Chicago, Illinois. The virgin aggregates were also scanned. High-resolution and three-dimensional images of the inside of these aggregates were obtained. Specialized software was used to analyze data, including void spaces. A porosity analysis of the investigated aggregates demonstrated that freeze/thaw and soundness tests significantly increased the connected pore space and induced cracks in the solid material. The analysis also demonstrated there is no trend or correlation between the increase in pore space resulting from freeze/thaw and that induced by the sodium sulfate soundness test.

REFERENCES

1. Weyers, R.E., Williamson, G.S., Mokarem, D.W., Lane, D.S., and Cady, P.D., "Testing Methods to Determine Long Term Durability of Wisconsin Aggregate Resources, Wisconsin Highway Research Program SPR# 0092-02-03, WHRP 06-07, October 2005.
2. Haider, W., Chatti, K., Buch, N., Lyles, R.W., Pulipaka, A.S., and Gilliland, D., "Statistical Analysis of In-Service Pavement Performance Data for LTPP SPS-1 and SPS-2 Experiments," Journal of Transportation Engineering, ASCE, Vol. 133, No. 6, June 2007, pp. 378-388.
3. Lee, Y.H., Kim, J.R., Daehyeon, K., and Kang, H.B., "New Approach for Estimating Rock Slope Stability Using Logistic Regression Analysis," Transportation Research Record, No. 2016, 2007, pp. 99-109.
4. Lai, S.-Y., Chang, W.-J., and Lin, P.-S., "Logistic Regression Model for Evaluating Soil Liquefaction Probability Using CPT Data," Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 132, No. 6, June 2006, pp. 694-704.
5. Chen, F., Akturk, O., and Drumm, E.C., "Simulation of Graded Rock Fill for Sinkhole Repair in Particle Flow Model," Underground Construction and Ground Movement (GSP 155), ASCE, 2006, pp. 104-111.
6. Liu, L, Brill, E.D., Mahinthakumar, G., and Ranjithan, S., "Contaminant Source Characterization Using Logistic Regression and Local Search Methods," World Environmental and Water Resources Congress, ASCE, 2008.
7. Hunt, L., “Micro-Deval Coarse Aggregate Test Evaluation: Final Report,” OR-RD-01-13, S. 547. Oregon Department of Transportation Research Group, Salem, OR, 2001.
8. Jayawickrama, P.W., Hossain, M.S., and Phillips, F., “Evaluation of Aggregate Durability Using Micro-Deval Test,” Paper published in the Compendium of Papers CD-ROM, 85th Annual Meeting of the Transportation Research Board, Washington D.C., January 22-26, 2006.
9. Lang, A.P., Range, P.H., Fowler, D.W., and Allen, J.J., "The Prediction of Coarse Aggregate Performance by Micro-Deval and Other Soundness, Strength, and Intrinsic Particle Property Tests,” 14th Annual Symposium, International Center for Aggregate Research, Texas, 2006.

10. Hossain, M.S., Lane, D.S., and Schmidt, B.N., "Use of the Micro-Deval Test for Assessing the Durability of Virginia Aggregates," Report No. VTRC 07-R29, Virginia Transportation Research Council, April 2007.
11. Rogers, C.A., Bailey, M.L., and Price, B. “Micro-Deval Test for Evaluating the Quality of Fine Aggregate for Concrete and Asphalt, Transportation Research Record 1301, TRB, National Research Council, Washington DC, 1991, pp. 68-76.
12. Hudec, P.P., and Boateng, S., “Quantitative Petrographic Evaluation of Fine Aggregates,” Cement, Concrete, and Aggregates, Vol. 17, No. 2, 1995, pp. 107-112.
13. White, T.D., Haddock, J.E., and Rismantojo, E., "Aggregate Tests for Hot-Mix Asphalt Used in Pavement," NCHRP report No. 557, Transportation Research Board, Washington DC, 2006.
14. Cooley, LA, and James, R.S., “Micro-Deval Testing of Aggregates in the Southeast,” In Transportation Research Record: Journal of the Transportation Research Board, No. 1837, TRB, National Research Council, Washington D.C., 2003, pp. 73-79.
15. Senior, S.A and Rogers, C.A., “Laboratory Tests for Predicting Coarse Aggregate Performance in Ontario,” Transportation Research Board 1301, National Research Council, Washington DC, 1991, pp. 97-106.
16. Lane, B.C., Rogers, C.A., and Senior, S.A., “The Micro-Deval Test for Aggregates in Asphalt Pavement,” Presented at the 8th Annual Symposium of the International Center for Aggregate Research. Denver, Colorado. April 12-14, 2000.
17. Rogers, C.A., Senior, S.A., and Boothe, D., “Development of an Unconfined Freeze/thaw Test for Coarse Aggregates,” Report EM-87, Ministry of Transportation, Ontario, 1989.
18. Rangaraju, P.R., and Edlinski, J., “Comparative Evaluation of Micro-Deval Abrasion Test with Other Toughness/Abrasion Resistance and Soundness Tests,” Journal of Materials in Civil Engineering, ASCE, Vol. 20 , No. 5, 2008, pp. 343-351.
19. Cuelho, E., Mokwa, R., Obert, K., and Miller, A. “Comparative Analysis Of Coarse Surfacing aggregate Using Microdeval, LA Abrasion And Sodium Sulfate Soundness Tests”, Final Report, FHWA/MT-06-016/8117-27, Montana State University, February 2007.
20. Tarefder, R.A., Zaman, M., and Hobson, K. “Micro Deval Test for Evaluating Properties of Roadway Aggregate”, International Journal of Pavements, 2003, pp 8-19.

21. Rogers, C.A., and Senior, S.A., “Recent Developments in Physical Testing of Aggregates to Ensure Durable Concrete,” Advances in Cement and Concrete, Proceedings of the Engineering Foundation Conference, 1994, pp. 338-361.
22. Saeed, A. Hall, J. W., and Barker, W., “Performance-Related Test of Aggregates for Use in Unbound Pavement Layers,” NCHRP Report No. 453. Washington D.C., National Academy Press, 2001.
23. Cooley, L. A. J., Huner, M.S. and James, R.H., “Micro-Deval Testing of Aggregates in the South East,” National Center for Asphalt Technology (NCAT) Report No. 02-09. Aulburn, Alabama, 2002.
24. Rangaraju, P.R., Edlinski, J., and Amirkhanian, S., "Evaluation of South Carolina Aggregate Durability Properties," FHWA-SC-05-01, South Carolina Department of Transportation, 2005.
25. Colorado Department of Transportation, "Standard Specification for Road and Bridge Construction," Section 703, aggregate for plant mix pavement, 2006.
26. Woodhouse, T., “Multi-State Coarse Aggregate Freeze/thaw Comparison,” Research Report No. R-1469, Michigan Department of Transportation, 2005.
27. Vose Software, “Model Risk” software, http://www.vosesoftware.com/.
28. Oracle, “Crystal Ball” software, http://www.oracle.com/us/products/applications/crystalball/overview/index.html.
29. Fowler, D.W., Allen, J.J., Lange, A., and Range, P., “The Prediction of Coarse Aggregate Performance by Micro-Deval and Other Aggregate Tests,” Report ICAR 507-1F, International Center for Aggregate Research, University of Texas, Austin, 2006.

APPENDIX A
END NOTE BIBILIOGRAPHY

1. (2005), "Milwaukee Public Museum." Retrieved March 2005, 2005, from http://www.mpm.edu/collect/geology/geosec-noframes.html.

2. AASHTO (2000), “Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II- Tests,” AASHTO HM-17 PT II TOC.

3. AASHTO (2002), “Resistance to Degradation of Small-size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine,” AASHTO T 96-02.

4. AASHTO (2007), “Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate,” AASHTO T 104-99.

5. AASHTO (2008), “Soundness of Aggregate by Freezing and Thawing,” AASHTO T 103-08.

6. AASHTO (2009), “Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus,” AASHTO T 327-09.

7. Abou-Zeid, M. N., and Cross, S. A. (1996), “Rapid Thermal Analysis Technique for Aggregate in Portland Cement Concrete,” K-TRAN:KU-96-1, University of Kansas.

8. Abrams, D. A. (1918), “Design of Concrete Mixtures,” Bulletin 1, Chicago, Structural Material Research Laboratory.

9. Alford, T. E., and Janssen, D.J . (1995), "Calibrating the Washington Hydraulic Apparatus," Transportation Research Record 1486: 124-148.

10. McDaniel, R., and Anderson, R. M. (2001), “Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual,” NCHRP Report # 452.

11. Arroyo, M. E., J., Sanmartin, I., and Lloret, A. (2008). “Size Effect on Tire Derived Aggregate Mechanical Properties,” International Workshop on Scrap Tire Derived Geomaterials-Opportunities and Challenges Barcelona Spain.

12. Assaad, J. K., and Kamal H. (2005), "Effect of Coarse Aggregate Characteristics on Lateral Pressure Exerted by Self-Consolidating Concrete," ACI Materials Journal 102: 145-153.

13. ASTM (1991), “Annual Book of ASTM Standards,” Philadelphia, PA, ASTM.

14. ASTM (1994), “Standard Practice for Evaluation of Frost Resistance of Coarse Aggregates in Air-Entrained Concrete by Critical Dilation Procedures,” ASTM C 682-94.

15. ASTM (2003), “Standard Test Method for Aggregate Durability Index,” ASTM D3744-03.

16. ASTM (2004), “Standard Test Method for Lightweight Particles in Aggregate,” ASTM C 123-04.

17. ASTM (2005), “Standard Test Method for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate,” ASTM C 88-05.

18. ASTM (2006), “Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine,” ASTM C 131-06.

19. ASTM (2007), “Standard Test Method for Density (Specific Gravity), and Absorption of Coarse Aggregate,” ASTM C127-07.

20. ASTM (2007), “Standard Test Method for Potential Alkali Reactivity of Aggregate (Mortar-Bar Method),” ASTM C 1260-94.

21. ASTM (2007), “Standard Test Method for Specific Gravity and Absorption of Fine Aggregate,” ASTM C 128-07a.

22. ASTM (2008), “Standard Specification for Concrete Aggregates,” ASTM C33/C 33M-08.

23. ASTM (2008), “Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing,” ASTM C 666 /C 666M-03.

24. ASTM (2008), “Standard Test Method for Slake Durability of Shales and Similar Weak Rocks,” ASTM D4644-08.

25. Babei, K., and Purvis, R., (1994), “Prevention of Cracks in Concrete Bridge Decks: Report on Laboratory Investigation of Concrete Shrinkage,” Report for Research Project 89-01, Pennsylvania Department of Transportation.

26. Barksdale, R. D. (1991), “The Aggregate Handbook,” Washington D.C., National Stone Association.

27. Barra, M., and V., E. (1998), "Properties of Concrete with recycled Aggregates: Influence of Properties of the Aggregates and Their Interpretation," Sustainable Construction: Use of Recycled Aggregate: 19-30.

28. Bennert, T. M., Ali, Bryant, Matthew, and Smith, Joseph (2006), "Comparing Fine Aggregate Angularity with Aggregate and Hot-Mix Asphalt Performance Test,"

Transportation Research Record 1962 (Non-bituminous Components of Bituminous Paving Mixtures): 79-89.

29. Brittnacher, D., Eggen, P. R. (2004), “Determination of Influences on Support Strength or Crushed Aggregate Base Course due to Gradational, Regional and Source Variations,” Wisconsin Highway Research Program.

30. Brown, B. A. (1999), “Aggregate Sources of the Sinnipee Group in Eastern and Southern Wisconsin,” Open File Report 1999-07, Wisconsin Department of Transportation.

31. Canadian Standards Association (2000), “Standard Practice to Identify Degree of Alkali-Aggregate Reactivity of Aggregates and to Identify Measures to Avoid Deleterious Expansion in Concrete,” CSA A 23-27A.

32. Chen, F., Akturk, O., and Drumm, E.C. (2006), "Simulation of Graded Rock fill for Sinkhole Repair in Particle Flow Model," Underground Construction and Ground Movement 104-111.

33. Clowers, K. (1991), “Seventy-Five years of Aggregate Research in Kansas,” FHWA-KS-99-1, Kansas Department of Transportation

34. Cominsky, R., Leahy, R. B., and Harrigan, E. T. (1994) “Level One Mix Design Material Selection, Compaction and Conditioning,” SHRP a-408, Washington D.C., Strategic Highway Research Program, National Research Council.

35. Cooley Jr, L. A., Huner, M.S. and James, R.H. (2002), “Micro-Deval Testing of Aggregates in the South East,” NCAT Report # 02-09, Aulburn, Alabama.

36. Cooley Jr, L. A., and James, R. S. (2003), "Micro-Deval Testing of Aggregates in the Southeast," Transportation Research Record: 73-79.

37. Correia, A. G. (1999), “Unbound Granular Materials: Laboratory Testing, In-Situ Testing and Modeling,” Proceedings of an international Workshop on Modeling and Advanced Testing for Unbound Granular materials, Balkema, Rotterdam: 231.

38. Cross, S. A., Smith, B. J., and Clowers, K. A. (1994), "Evaluation of Fine Aggregate Angularity Using National Aggregate Association Flow Test," Transportation Research Record 1437: 43-50.

39. Cuelho, E., Mokwa, R., Obert, K., and Miller, A. (2008), “Comparative Analysis of Micro-Deval, LA Abrasion and Sulfate Soundness Tests,” 87th Annual Meeting Compendium of Papers, Transportation Research Board.

40. Dauod, O. E. K. (1990), "Properties and Reactivity of Gabbro and Harsburgite Gravels Used in Concrete Work in Kuwait," ACI Materials Journals: 446-456.

41. DeMerchant, D. P., Fournier, B., and Strang, F. (2000), "Alkali-Aggregate Research in New Brunswick," Canadian Journal of Civil Engineering 27: 212-225.

42. Desai, S. B. (1998), "Sustainable Development and Recycling of Concrete Aggregate," Sustainable Construction: Use of Recycled Aggregate: 381-388.

43. Dubberke, W., and Marks, V. J. (1984), “The Relationship of Aggregate Durability to Trace Element Content,” HR-266, Iowa Department of Transportation.

44. Dubberke, W., and Marks, V. J. (1994), “Thermogravimetric Analysis of Carbonate Aggregate,” Project HR-336, Ames, Iowa, Office of Materials, Highway Division, Iowa Department of Transportation.

45. Ehn, A. L. (2002), “Evaluation of Portland Cement Concretes-Blast Furnace Slag,” Akron, OH, University of Akron.

46. Embacher, R. A., and Snyder, M. B. (2003), "Refinement and Validation of the Hydraulic Fracture Test," Transportation Research Record 1837: 80-88.

47. Folliard, K. J. (2004), “Assessing Aggregate Reactivity Using the Accelerated Concrete Prism Test,” ICAR 12th Annual Symposium. Denver Colorado.

48. Folliard, K. J., and Smith, K. D. (2003), “Aggregate Test for Portland Cement Concrete Pavements,” Research Reports Digest No 281, National Cooperative Highway Research Program.

49. Frohnsdoff, G., and Clifton, J. (1995), “Cement and Concrete Standards of the Future,” Workshop on Cement and Concrete Standards Report.”

50. Gullerud, K., and Cramer, S. (2002), “Effects of Aggregate Coatings and Films on Concrete Performance,” WHRP #0092-22-07, Madison Wisconsin, University of Wisconsin.

51. Haider, W., Chatti, K., Buch, N., Lyles, R. W., Pulipaka, A. S., and Gilliland, D. (2007), "Statistical Analysis of In-service Pavement Performance Data." Journal of Transportation Engineering, ASCE 133: 378-388.

52. Harman, J. W., Cady, P. D., and Bolling, N. B. (1970), "Slow-Cooling Test for Frost Susceptibility of Pennsylvania Aggregates," Highway Research Record: 26-37.

53. Hellmuth, R., Stark, D., Diamond, S., and Moranville-Regoud, M. (1993), “Alkali-Silica Reactivity: Overview Research,” SHRP-C-342, Washington D.C., Strategic Highway Research Program.

54. Hossain, M. S., Lane, D. S., and Schmidt, B. N. (2007), “Use of the Micro-Deval Test for Assessing the Durability of Virginia Aggregates,” Report No VTRC 07-R29, Virginia Transportation Research Council: 30.

55. Hossain, M. S., Lane, D. S., and Schmidt, B. N. (2008), "Use of the Micro-Deval Test for Assessing Fine Aggregate Durability," Transportation Research Record 2059: 11-19.

56. Hossain, M. S., Parker, F., and Kandhal, P. S. (2000), "Uncompacted Voids and Particle Index Tests for Evaluating Coarse Aggregate," Transportation Research Record 1721: 100-105.

57. Hunt, L. (2001), “Micro-Deval Coarse Aggregate Test Evaluation,” Final Report SH 547. Salem, Oregon Department of Transportation Research Group.

58. Issa, M. A., and Bendok, M. (2000), "Modified Washington Hydraulic Fracture Test to Determine D-Cracking Susceptible Aggregate," Cement, Concrete and Aggregates 116-127.

59. Janssen, D. J., and Snyder, M. B. (1994), “Resistance of Concrete to Freezing and Thawing,” SHRP-C-391, Washington D.C., Strategic Highway Research Program, National Research Council.

60. Kandhal, P. S. (1998), “Aggregate Test Related to Asphalt Concrete Performance in Pavements,” Report No 405. Washington D.C., Transportation Research Board, National Research Council, National Cooperative Research Program.

61. Kandhal, P. S. (2001), “The Restricted one in the Superpave Aggregate Gradation Specification,” NCHRP No 464, Washington D.C., Transportation Research Board, National Research Council, National Cooperative Research Program.

62. Kolisoja, P., Saarenketo, T., Peltomiemi, H., and Vuorimies, N. (2000), "Testing of Suction and Deformation of base Aggregates," Transportation Research Record 1787: 83-89.

63. Koubaa, A., and Snyder, M.b., (2001), "Assessing frost Resistance of Concrete Aggregates in Minnesota," Journal of Cold Regions Engineering 15: 187-210.

64. Kuo, S. S., Mahgoub, H.S., and Nazef, A. (2002), "Investigation of Recycled Concrete Made with Limestone," Transportation Research Record 1787: 99-108.

65. Lai, S. Y., Chang, W.J., and Lin, P. S., (2006), "Logistic Regression Model for Soil Liquefaction," Journal of Geotechnical and Geoenviromental Engineering, ASCE 132: 694-704.

66. Lane, D. S. (1993), "Experience with ASTM P 214 in Testing Virginia Aggregates," Transportation Research Record 1668: 42-47.

67. Lane, D. S. (2000), “Alkali-Silica Reactivity in Virginia, USA: Occurrences and Reactive Aggregate,” Alkali Reaction in Concrete, 11th International Conference: 385-394.

68. Lang, A. P., Range, P.H., Fowler, D.W., and Allen, J.J. (2006), “The prediction of Coarse Aggregate Performance by Micro-Deval and Other Soundness, Strength and Intrinsic Particle Property tests,” 14th Annual Symposium, International Center for aggregate Research, Texas.

69. Larson, T. D., and Cady, P. D. (1969), “Identification of Frost-Susceptible Particles in Concrete Aggregates,” NCHRP Report No 66, Washington D.C., Highway Research Board.

70. Lee, Y. H., Kim, J.R., Daehyeon, K., and Kang, H.B. (2007), "New Approach for Estimating Rock Slope Stability Using Logistic Regression Analysis," Transportation Research Record 2016: 99-109.

71. Liu, L., Brill, E. D., Mahinthakumar, G., and Ranjithan, S., (2008), "Contaminant source characterization Using Logistic Regression," World environmental and Water Resources Congress

72. Lo, C. Y. T., Vivian W.Y., and Kotrayothar, D (2009), "A simplified Testing Approach for Recycled Coarse Aggregate in Construction," Transactions Hong Kong Institution of Engineers 16: 43-47.

73. Lu, D., Fournier, B., and Grattan-Bellew, P. (2006), "Effect of Aggregate Particle Size on Determining Alkali-Silica Reactivity by Accelerated Tests," Journal of ASTM international, Volume 3, Issue 9.

74. Lynn, T., James, R. S., Wu, P. Y., and Jared, D. M. (2007), "Effect of Aggregate Degradation on Volumetric Properties of Georgia's Hot-Mix Asphalt," Transportation Research Record 1998: 123-131.

75. Mao, J., Koichi, A., Qi, H., and Liu, Z. (2010), "Experimental Study on Freeze/thaw Damage," Journal of ASTM International, Volume 7, Issue 1.

76. Mao, J., and Ayuta, K. (2008), "Freeze/thaw Resistance of Lightweight Concrete and Aggregate," Journal of Materials in Civil Engineering, ASCE, Volume 20, SPECIAL ISSUE: Durability and Service Life of Concrete Structures: Recent Advances, p. 78-84.

77. Meininger, R. (2004), "Micro-Deval Vs. L. A. Abrasion," Rock Products.

78. Mills-Beale, J., You, Z., Williams, R. C., and Dai, Q. (2009), "Determining the Specific Gravities of Coarse Aggregate," Construction and Building Materials 23: 1319-1322.

79. Newlon, H. (1978), “Modifications of ASTM C 666 for Testing Resistance of Concrete to Freezing and Thawing in Sodium Chloride Solution,” VTRC 79-R16.

80. Novokschenov, V. (2006) “A cautionary Tale,” Civil Engineering 76, No. 1, p 46-51.

81. Nurse, R. W. (1968), “Cohesion and Adhesion in Solids,” The Structure of Concrete, Proceedings of an International Conference, London, Cement and Concrete Association.

82. OECD (1991), “Recycling Strategies for Road Works,” Paris, France, Organization for Economic Cooperation and Development

83. Phileo, R. E. (1986), “Freezing and Thawing Resistance of High Strength Concrete,” NCHRP Synthesis Report # 129, Transportation Research Record.

84. Phillips, W. F. (2000), “Comparative Analysis Between the Magnesium Sulfate Soundness,” Texas Tech University.

85. Pigeon, M., and Pleau, R. (1995), “Durability of Concrete in Cold Climates,” Taylor & Francis.

86. Powers, T. C. (1955), "Basic Considerations Pertaining to Freezing and Thawing Tests," ASTM 55(Proceedings).

87. Rangaraju, P. R., and Edlinski, J. (2008), "Comparative Evaluation of Micro-Deval Test with Other Abrasion and Soundness Test," Journal of Materials in Civil Engineering ASCE: 343-351.

88. Primel, L., and Toutenq, C. (2000), "Aggregates: Geology, Prospection, Environment, Testing, Specifications, Extraction, Processing Plants, Equipments, Quality Control," Balkema.

89. Randy B. Foltz, G. L. E., and Mark Truebe "Relationship of Forest Road Aggregates Test Properties to Sediment Production,": Section: 16, Chapter:12.

90. Rangarahu, P. R., Edlinski, J., and Amirkhanian, S. (2005), “Evaluation of South Carolina Aggregate Durability Properties,” FHWA-SC-05-01, South Carolina Department of Transportation.

91. Rismantojo, E. (2002), “Permanent Deformation and Moisture Susceptibility West Lafayette,” Purdue University Ph.D.

92. Rogers, C., Gorman, B. and Lane, B. (2002), “Skid-Resistance Aggregates in Ontario,” Proceedings of the 10th Annual Symposium International Center for Aggregates Research

93. Rogers, C. A. and Senior, S. A. (1991), "Laboratory Test for Predicting Coarse Aggregate Performance in Ontario," Transportation Research Record 1301: 97-106.

94. Rogers, C. A., Bailey, M. L., and Price, B. (1991), "Micro-Deval Test for Evaluating the Quality of Fine Aggregate for Concrete and Asphalt," Transportation Research Record 1301: 68-76.

95. Ryskewitsch, E. (1953), "Compression Strength of Porous Sintered Alumina and Zirconia," 9th Communication to Ceramography, Journal of the American Ceramic Society 36: 65-68.

96. Saeed, A., Hall, J. W., and Barker, W. (2001), "Performance-Related Test of Aggregates for Use in Unbound Pavement Layers," NCHRP Report #453. Washington D.C., National Academy Press.

97. Scullion, T., and Saarenketo, T. (1995), "Using Suction and Dielectric Measurements as Performance Indicators for Aggregate Base Materials," Transportation Research Record 1577: 37-44.

98. Rogers, C. A., and Senior, S. A. (1994), "Recent Developments in the Physical Testing of Aggregate," Advances in Cement and Concrete: Proceedings of an Engineering foundation conference, pp. 338-361.

99. Amirkhanian, S. N., Kaczmarek, D., and Burati Jr, J. L. (1991), "Effects of Los Angeles Abrasion Test Values on Prepared Marshall Specimens," Transportation Research Record 1301: 77-86.

100. Sheftick, W. (1998), "Sodium Sulfate Test Evaluation," Cement, Concrete and Aggregates 11.

101. Shen, A., Xiong, J., He, J., and Liu, T. (2009) "Study on the Influence of Coarse Aggregate on the Pavement Performance of Road Cement Concrete," ASCE, from http://ascelibrary.org/doi/pdf/10.1061/41064(358)42.

102. Stark, D. (1976), "Characteristics and Utilization of Coarse Aggregate Associated with D-Cracking," Bulletin RD047.07P. Skokie, IL, Portland Cement Association.

103. Stark, D., Morgan, B., Paul, O., and Diamond, S (1993), "Eliminating or minimizing Alkali-Silica Reactivity," SHRP-C-343. Skokie, IL, Strategic Highway Research Program.

104. Syed, I., Scullion, T., and Randolph, R.B., (2000), "Tube Suction Test for Evaluation of Aggregate Base Materials in Frost/Moisture Susceptible Environment," Transportation Research Record 1709(00-1147).

105. Tam, Vivian W. Y., and Le, Khoa N. (2007), "Aggregate Testing Using 2nd, 7th and 10th-order Interpolation polynomials," Conservation and Recycling 52: 39-57.

106. Tam, Vivian W. Y., and Le, Khoa N. (2007), "Optimal aggregate Testing Using Vandermonde Polynomials and Spectral Methods," Journal of Hazardous Materials 145: 72-99.

107. Tarefder, R. A., Zaman, M., and Hobson, K. (2003), "Micro Deval Test for Evaluating Properties of Roadway Aggregate," International Journal of Pavements 2: 8-19.

108. Tauma, W. E., and Fowler, D. W. (2001), "Characterizing Alkali-Silica Reactivity of Aggregates Using ASTM C 1293, ASTM C 1260 and Their Modifications," Transportation Research Record 1757: 157-165.

109. Ruth, B. E., and Tia, M. (1998), "Aggregate Degradation Testing by Gyratory Testing Machine," Transportation Research Record 1619: 3-10.

110. Titi, H., Tabatabai, H., Ghorbanpoor, A., Lamichhane, K., and Elias, M., (2004), “The effect of Minnesota Aggregate on Rapid Chloride Permeability,” Test Report No. 2005-10, Minnesota Department of Transportation.

111. Tremper, B., and Spellman, D. L. (1961), “Test for Freezing-Thaw Durability of Concrete Aggregates,” Bulletin 305, National Research Council, Washington D.C.

112. Tutumluer, E. (2008), “State of the Art: Anisotropic Characterization of Unbound Aggregate Layers in Flexible Pavements,” Proceedings of the Symposium on Pavement Mechanics and Materials at the Inaugural International Conference of the Engineering Mechanics Institute- Pavements and materials 2008.

113. Tutumluer, E., and Pan, T. (2008), "Aggregate Morphology Affecting Strength and Permanent Deformation behavior of Unbound Aggregate Materials," Journal of Materials in Civil Engineering 20: 617-627.

114. Vasiliu, D. (1982), "Characteristic Water of Aggregate Testing and Applications," Materiaux et Constructions 15: 185-194.

115. Verback, G., and Landgren, R. (1960) "Influence-Physical Characteristics of Aggregate on Frost Resistance," Proceedings, ASTM: 1063-1079.

116. Vogler, R. H., and Grove, G. H. (1989), "Freeze/thaw Testing of Coarse Aggregate in Concrete: Procedures Used by Michigan Department of Transportation and Other Agencies," Cement, Concrete and Aggregates 11: 57-66.

117. Watson, D. E., Masad, E., Moore, K. A., Williams, K., and Cooley Jr, L. A. (2004), "Verification of Voids in Coarse Aggregate Testing: Determining stone-on-stone Contact of Hot Mix Asphalt's Mixtures," Transportation Research Record 1891: 182-190.

118. Weyers, R. E., Williamson, G. S, Mokarem, D. W., Lane, D. S., and Cady, P. D., (2005), “Testing Methods to Determine Long Term Durability of Wisconsin Aggregate Resources,” SPR # 0092-02-03, Wisconsin Highway Research Program.

119. White, T. D., Haddock, J.E., and Rismantojo, E. (2006), “Aggregate Test for Hot-Mix Asphalt Used in Pavement,” NCHRP report No 557, Washington, Transportation Research Boar.

120. Won, M. C. (2004), “Use of Crushed Concrete as Aggregate for Pavement Concrete,” Report 1753-1F, TxDOT.

121. Won, M. C., and Fu, C. N. (1996), "Evaluation of Laboratory Procedures for Aggregate polish Test," Transportation Research Record 1547: 23-28.

122. Woodhouse, T. (2005), “Multi-State Coarse Aggregate Freeze/thaw Comparison,” Research Report R-1469, Michigan Department of Transportation.

123. Woodward, W. D. H. (1995), “Laboratory Prediction of Surfacing Aggregate Performance,” Jordanstown, Newtownabbey, County Anthim, Northern Ireland, University of Ulster. Ph.D.

124. Wu, Y., Parker, F., and Kandhal, K. (1998), “Aggregate Toughness/Abrasion Resistance and Durability/Soundness Test Related to Asphalt Concrete Performance in Pavements,” NCAT Report # 98-4. Auburn, Al.

125. Zhang, J. L., and Lin, Q. W. (2005), "Effect of Coarse Aggregate Size on Relationship Between Stress and Crack Opening in Normal and High Strength Concretes," Journal of materials Science Technology 21: 691-700.

126. Zubery, M. H., and Hossain, M. (1996), “Correlation of KDOT and SHRP's Washington Hydraulic Fracture Index (WHFI) Aggregate Durability Test Methods,” K-TRAN: KSU 94-5, Kansas State University.

APPNDIX B
TEST RESULTS

Relative Density and Absorption Results

$$OD = \frac{A}{B - C}$$

$$SSD = \frac{B}{B - C}$$

$$Absorption = \left[\frac{(B - A)}{A}\right] x100$$

$OD = Relative\ Density\ on\ the\ basis\ of\ oven - dry\ aggregate$

$SSD = Relative\ Density\ on\ the\ basis\ of\ saturated - surface\ dry\ aggregate$

$A = mass\ of\ oven - dry\ test\ samplein\ air$

$B = mass\ of\ saturated - surface\ dry\ test\ sample\ in\ air$

$C = Apparent\ mass\ of\ saturated\ test\ sample\ in\ water$

	Weight Wire Basket (g)	Weight Saturated Dry Surface + Basket (g)	Submerged Weight + Basket (g)	Weight Oven Dry + Basket (g)	A (g)	B (g)	C (g)	Relative Density (OD)	Relative Density (SSD)	Absorption (%)
C.C Linck	1030	6246.3	4189.5	6059.5	5029.5	5216.3	3159.5	2.4453	2.5361	3.7141
Hanz-Brothers Johnson	1030	7137.1	4758.4	6970.5	5940.5	6107.1	3728.4	2.4974	2.5674	2.8045
Oak Park	1030	5766.3	3890.4	5629.4	4599.4	4736.3	2860.4	2.4518	2.5248	2.9765
Kaupanger-Ramsey	1030	6129.8	4150.3	6000.7	4970.7	5099.8	3120.3	2.5111	2.5763	2.5972
Dane County	1030	6121.1	4124.8	6023.2	4993.2	5091.1	3094.8	2.5012	2.5503	1.9607
Utica-Feggestead	1030	6157	4151.5	6040.8	5010.8	5127	3121.5	2.4985	2.5565	2.3190
K-Quarry	1030	5950.2	3965.2	5856.5	4826.5	4920.2	2935.2	2.4315	2.4787	1.9414
Swiggian	1030	7134	4656.7	6895.1	5865.1	6104	3626.7	2.3675	2.4640	4.0732
Schaefer	1030	6617.1	4365.6	6451.6	5421.6	5587.1	3335.6	2.4080	2.4815	3.0526
Ebenezer	1030	6369.1	4203.2	6218.1	5188.1	5339.1	3173.2	2.3954	2.4651	2.9105
Krogman	1030	7734.8	5105.4	7597.6	6567.6	6704.8	4075.4	2.4978	2.5499	2.0890
Scheneider	1030	7576.9	4986.7	7419.8	6389.8	6546.9	3956.7	2.4669	2.5276	2.4586

LA Abrasion Test Results

C.C. Linck

	Container	Sample + container	Weight Sample
1/2" - 3/4"	594.5	3100.5	2506
3/8" - 1/2"	642.5	3141.9	2499.4
		Initial Mass	5005.4
		Final Mass	3174.5
		Loss (%)	**37**

	Container	Sample + container	Weight Sample
Larger than 1.70mm	600.2	3774.7	3174.5
Smaller than 1.70mm	642.5	2463.9	1821.4

Hanz-Brothers

	Container	Sample + container	Weight Sample
1/2" - 3/4"	600	3103.1	2503.1
3/8" - 1/2"	642.5	3158.8	2516.3
		Initial Mass	5019.4
		Final Mass	3502.3
		Loss (%)	**30**

	Container	Sample + container	Weight Sample
Larger than 1.70mm	600	4102.3	3502.3
Smaller than 1.70mm	597.1	2131.9	1534.8

Oak Park

	Container	Sample + container	Weight Sample
1/2" - 3/4"	599	3101.1	2502.1
3/8" - 1/2"	600	3102	2502
		Initial Mass	5004.1
		Final Mass	3438.2
		loss (%)	**31**

	Container	Sample + container	Weight Sample
Larger than 1.70mm	597.5	4035.7	3438.2
Smaller than 1.70mm	600	2176.2	1576.2

Ramsey

	Container	Sample + container	Weight Sample
1/2" - 3/4"	600	3108	2508
3/8" - 1/2"	597.6	3101.8	2504.2
		Initial Mass	5012.2
		Final Mass	3224.1

Loss (%)	**36**

	Container	Sample + container	Weight Sample
Larger than 1.70mm	597.5	3821.6	3224.1
Smaller than 1.70mm	600	2359.7	1759.7

Dane County

	Container	Sample + container	Weight Sample
1/2" - 3/4"	596.5	3099.1	2502.6
3/8" - 1/2"	600	3103.5	2503.5
		Initial Mass	5006.1
		Final Mass	3074.5

Loss (%)	**39**

	Container	Sample + container	Weight Sample
Larger than 1.70mm	767.8	3842.3	3074.5
Smaller than 1.70mm	781.9	2564.8	1782.9

Utica

	Container	Sample + container	Weight Sample
1/2" - 3/4"	597	3105.3	2508.3
3/8" - 1/2"	600	3098.5	2498.5
		Initial Mass	5006.8
		Final Mass	3190.6

Loss (%)	**36**

	Container	Sample + container	Weight Sample
Larger than 1.70mm	597.3	3787.9	3190.6
Smaller than 1.70mm	600	2379.6	1779.6

K-Quarry

	Container	Sample + container	Weight Sample
1/2" - 3/4"	337.5	2836.9	2499.4
3/8" - 1/2"	309.7	2806.4	2496.7
		Initial Mass	4996.1
		Final Mass	3924.2

loss (%)	**21**

	Container	Sample + container	Weight Sample
Larger than 1.70mm	337.7	4261.9	3924.2
Smaller than 1.70mm	309.3	1388.2	1078.9

Swiggan

	Container	Sample + container	Weight Sample
1/2" - 3/4"	336.8	2836.2	2499.4
3/8" - 1/2"	308.8	2804	2495.2
		Initial Mass	4994.6
		Final Mass	2940.6

loss (%)	**41**

	Container	Sample + container	Weight Sample
Larger than 1.70mm	1262.8	4203.4	2940.6
Smaller than 1.70mm	1299.2	3358.4	2059.2

Scheafer

	Container	Sample + container	Weight Sample
1/2" - 3/4"	340	2845.3	2505.3
3/8" - 1/2"	310	2804.4	2494.4
		Initial Mass	4999.7
		Final Mass	2975

loss (%)	**40**

	Container	Sample + container	Weight Sample
Larger than 1.70mm	336.9	3311.9	2975
Smaller than 1.70mm	309	2265.7	1956.7

Ebenezer

	Container	Sample + container	Weight Sample
1/2" - 3/4"	336.8	2837.3	2500.5
3/8" - 1/2"	308.8	2808	2499.2
		Initial Mass	4999.7
		Final Mass	3318.8

Loss (%)	**34**

	Container	Sample + container	Weight Sample
Larger than 1.70mm	336.4	3655.2	3318.8
Smaller than 1.70mm	308.5	1930.2	1621.7

Krogman

	Container	Sample + container	Weight Sample
1/2" - 3/4"	338.1	2836.6	2498.5
3/8" - 1/2"	309.9	2809.1	2499.2
		Initial Mass	4997.7
		Final Mass	3235.3

Loss (%)	**35**

	Container	Sample + container	Weight Sample
Larger than 1.70mm	337.5	3572.8	3235.3
Smaller than 1.70mm	309.8	2031.6	1721.8

Schneider

	Container	Sample + container	Weight Sample
1/2" - 3/4"	340	2839.4	2499.4
3/8" - 1/2"	310	2809.6	2499.6
		Initial Mass	4999
		Final Mass	3018.3

Loss (%)	**40**

	Container	Sample + container	Weight Sample
Larger than 1.70mm	340	3358.3	3018.3
Smaller than 1.70mm	310	2261.3	1951.3

Sodium Sulfate Soundness Tests (AASHTO T104)

C.C Linck (water Town)

	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve after test	Weighted % loss
1.5"-3/4"	37.90	3464.10	32.872	12.5
3/4"-3/8"	41.25	3770.2	19.905	8.2
3/8"-No4	20.85	1906	5.538	1.2
		9140.30		21.8

Hanz-Brothers Johnson

	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve after test	Weighted % loss
1.5"-3/4"	59.40	5980.10	13.882	8.2
3/4"-3/8"	37.54	3779.4	12.009	4.5
		9759.50		12.8

Oak Park (Deerfield)

	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve after test	Weighted % loss
1"-3/4"	11.02	542.10	4.807	0.5
3/4"-3/8"	73.01	3593	4.269	3.1
3/8"-No4	15.98	786.2	1.993	0.3
		4921.30		4.0

Kaupanger-Ramsey

	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve after test	Weighted % loss
1"-3/4"	12.39	495.90	0.200	0.0
3/4"-3/8"	56.14	2247.2	4.217	2.4
3/8"-No4	31.47	1259.4	1.051	0.3
		4002.50		2.7

Dane County				
	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve after test	Weighted % loss
1"-3/4"	40.99	3222.00	1.727	0.7
3/4"-3/8"	52.74	4145.8	0.796	0.4
3/8"-No4	6.27	493.1	0.954	0.1
		7860.90		1.2

Utica-Feggestead				
	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve after test	Weighted % loss
1"-3/4"	28.94	818.80	4.106	1.2
3/4"-3/8"	66.29	1875.7	7.215	4.8
		2694.50		6.0

K-Quarry				
	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve after test	Weighted % loss
1"-3/4"	26.11	787.90	0.814	0.2
3/4"-3/8"	50.41	1521.4	2.358	1.2
3/8"-No4	23.48	708.7	1.919	0.5
		3018.00		1.9

Swiggian				
	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve after test	Weighted % loss
1"-3/4"	5.88	458.10	1.224	0.07
3/4"-3/8"	26.73	2081.20	0.427	0.11
3/8"-No4	67.38	5245.40	0.072	0.05
		7784.70		0.23

Schaefer

	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve after test	Weighted % loss
1"-3/4"	9.42	483.00	0.234	0.02
3/4"-3/8"	68.06	3488.10	0.200	0.14
3/8"-No4	22.52	1154.30	0.067	0.02
		5125.40		0.17

Ebenezer

	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve after test	Weighted % loss
1"-3/4"	16.01	760.60	1.144	0.2
3/4"-3/8"	66.85	3176.90	3.443	2.3
3/8"-No4	17.14	814.50	2.499	0.4
		4752.00		2.9

Krogman

	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve after test	Weighted % loss
1"-3/4"	45.95	3638.00	0.047	0.022
3/4"-3/8"	51.73	4095.10	0.357	0.185
		7733.10		0.207

Schneider

	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve after test	Weighted % loss
1"-3/4"	7.38	528.70	1.128	0.1
3/4"-3/8"	65.73	4708.80	1.001	0.7
3/8"-No4	26.89	1926.50	0.156	0.0
		7164.00		0.8

Soundness of Aggregate by Freezing and Thawing (AASHTO T103)

C.C Linck (water Town)

	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve aftert test	Weighted % loss
1.5"-3/4"	27.14	3046.20	38.649	10.5
3/4"-3/8"	45.91	5153	22.432	10.3
3/8"-No4	26.96	3026	7.706	2.1
		11225.20		22.9

Hanz-Brothers Johnson

	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve aftert test	Weighted % loss
1.5"-3/4"	63.08	5798.20	37.056	23.4
3/4"-3/8"	36.27	3333.4	23.216	8.4
		9131.60		31.8

Oak Park (Deerfield)

	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve aftert test	Weighted % loss
1"-3/4"	6.32	304.30	19.680	1.2
3/4"-3/8"	88.33	4251.1	15.680	13.9
3/8"-No4	5.34	257.2	4.952	0.3
		4555.40		15.4

Ramsey

	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve aftert test	Weighted % loss
1"-3/4"	10.40	657.00	7.346	0.76
3/4"-3/8"	63.37	4004.1	9.545	6.05
3/8"-No4	26.23	1657.1	3.148	0.83
		6318.20		7.6

Dane County	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve aftert test	Weighted % loss
1 1/2"-3/4"	54.15	3738.20	0.464	0.25
3/4"-3/8"	37.01	2554.8	0.929	0.34
3/8"-No4	8.84	610.1	0.398	0.04
		6903.10		0.63

Utica-Feggestead	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve aftert test	Weighted % loss
1"-3/4"	40.04	2438.80	12.661	5.1
3/4"-3/8"	59.20	3606.3	15.064	8.9
		6045.10		14.0

K-Quarry	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve aftert test	Weighted % loss
1"-3/4"	20.33	942.00	8.489	1.7
3/4"-3/8"	48.52	2247.9	16.582	8.0
3/8"-No4	31.15	1443.10	6.74	2.1
		4633.00		11.87

Swiggian	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve aftert test	Weighted % loss
3/4"-3/8"	57.44	3341.5	0.645	0.4
3/8"-No4	39.65	2306.20	0.29	0.1
		5647.70		0.49

Schaefer	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve aftert test	Weighted % loss
1"-3/4"	8.09	571.50	4.692	0.4
3/4"-3/8"	59.24	4186.5	7.875	4.7
3/8"-No4	32.67	2309.10	1.98	0.6
		7067.10		5.69

Ebenezer	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve aftert test	Weighted % loss
1"-3/4"	14.03	712.50	23.779	3.3
3/4"-3/8"	67.64	3436.2	33.000	22.3
3/8"-No4	18.33	931.30	8.92	1.6
		5080.00		27.29

Krogman	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve aftert test	Weighted % loss
1"-3/4"	31.66	2077.50	2.506	0.8
3/4"-3/8"	66.82	4384.7	5.689	3.8
		6462.20		4.60

Schneider	Grading of Original sample (%)	Mass of the Fraction Before Test (g)	% Passing Designated Sieve aftert test	Weighted % loss
1"-3/4"	7.53	595.00	5.555	0.4
3/4"-3/8"	66.22	5232.5	3.632	2.4
3/8"-No4	26.25	2073.90	1.53	0.4
		7901.40		3.22

Micro-Deval Test Results

C.C. Linck	
Fraction	Mass (g)
3/4"-5/8"	375.5
5/8"-1/2"	374.3
1/2"-3/8"	752.2
Mass A	1502
Mass B	920.8
Loss (%)	**38.70**

Dane	
Fraction	Mass (g)
3/4"-5/8"	376.6
5/8"-1/2"	375.7
1/2"-3/8"	750.6
Mass A	1502.9
Mass B	1200.1
Loss (%)	**20.15**

Scheafer	
Fraction	Mass (g)
3/4"-5/8"	375.5
5/8"-1/2"	375.5
1/2"-3/8"	748.9
Mass A	1499.9
Mass B	1164.9
Loss (%)	**22.33**

Hanz-Brothers	
Fraction	Mass (g)
3/4"-5/8"	376.7
5/8"-1/2"	374.6
1/2"-3/8"	750
Mass A	1501.3
Mass B	1033.1
Loss (%)	**31.19**

Utica	
Fraction	Mass (g)
3/4"-5/8"	374.4
5/8"-1/2"	375.2
1/2"-3/8"	750.7
Mass A	1500.3
Mass B	1232.5
Loss (%)	**17.85**

Ebenezer	
Fraction	Mass (g)
3/4"-5/8"	374.7
5/8"-1/2"	376.6
1/2"-3/8"	750.2
Mass A	1501.5
Mass B	1048.5
Loss (%)	**30.17**

Oak Park	
Fraction	Mass (g)
3/4"-5/8"	375.5
5/8"-1/2"	375.4
1/2"-3/8"	748.2
Mass A	1499.1
Mass B	1232.5
Loss (%)	**17.78**

K-Quarry	
Fraction	Mass (g)
3/4"-5/8"	375.7
5/8"-1/2"	374.8
1/2"-3/8"	750
Mass A	1500.5
Mass B	1037.8
Loss (%)	**30.84**

Krogman	
Fraction	Mass (g)
3/4"-5/8"	373.2
5/8"-1/2"	376.5
1/2"-3/8"	750.2
Mass A	1499.9
Mass B	1235.6
Loss (%)	**17.62**

Ramsey	
Fraction	Mass (g)
3/4"-5/8"	374.5
5/8"-1/2"	375.5
1/2"-3/8"	750.6
Mass A	1500.6
Mass B	1241.6
Loss (%)	**17.26**

Swiggian	
Fraction	Mass (g)
3/4"-5/8"	375
5/8"-1/2"	375.2
1/2"-3/8"	750.2
Mass A	1500.4
Mass B	1193.3
Loss (%)	**20.47**

Schneider	
Fraction	Mass (g)
3/4"-5/8"	374.8
5/8"-1/2"	375.7
1/2"-3/8"	750
Mass A	1500.5
Mass B	1215.8
Loss (%)	**18.97**

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